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LIQUID TANKER STABILITY

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Un sommaire en français de ce rapport est inclus avant la table des matières.

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16. Abstract

Dynamic stability limits of partially filled tank vehicle combinations were investigated through computer simulation and field testing. Haulers and manufacturers across Canada were surveyed to select candidate vehicles and tank configurations. Overturning limits of tank vehicles were investigated using a kineto-static roll plane model. It was observed that tank vehicles with modified-oval and -square cross-sections exhibit lower overturning limits than those with circular cross-section tanks.

A three-dimensional tank-vehicle model, incorporating a steady-state fluid slosh model was developed and computer simulation was performed to determine directional stability for various manoeuvres, fill levels, vehicle speeds, and tank design factors. A comparison of directional response characteristics of tank vehicles with liquid and equivalent rigid cargo clearly demonstrated the adverse influence of fluid slosh.

A comprehensive dynamic fluid slosh model was developed and integrated to the vehicle model to investigate the influence of dynamic slosh loads on the dynamic stability of tank vehicles. Directional response characteristics of tank vehicles using dynamic and steady-state fluid slosh models illustrated that for typical highway manoeuvres, vehicle stability can be effectively predicted using the steady-state fluid slosh analysis.

The results from the computer simulation models were validated by comparing them with results from field tests conducted by the Ontario Ministry of Transport. Directional response predicted from the computer models showed good correlation with the field-measured data.

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16. Résumé

Cette étude a consisté à mettre en évidence par la modélisation et par des essais routiers les accélérations transversales limites de véhicules-citernes de configurations variées. Une enquête a été menée auprès des transporteurs et des constructeurs de matériels routiers pour connaître les configurations les plus répandues au Canada. Un modèle de comportement a été réalisé, intégrant un modèle dynamique-statique avec un modèle de tenue transversale. Il a été observé que les citernes de forme ovale modifiée ou carrée supportent des accélérations transversales limites inférieures aux citernes cylindriques.

Un modèle tridimensionnel de comportement dynamique intégrant un modèle de comportement en régime stable a été réalisé et utilisé pour mettre en évidence l'influence sur la stabilité directionnelle de facteurs tels que manoeuvres, niveaux de remplissage, vitesses de marche et architecture des citernes. La comparaison des caractéristiques de directibilité des véhicules-citernes avec des véhicules témoins transportant une cargaison rigide a fait ressortir l'influence pernicieuse du ballottement.

Un modèle global de comportement dynamique en ballottement a été réalisé et intégré au modèle tridimensionnel; il a servi à mettre en évidence l'influence du balancement de la cargaison sur la directibilité des véhicules-citernes. Les caractéristiques de directibilité des véhicules-citernes en régime dynamique et stable ont permis de déterminer que la stabilité des véhicules durant les manoeuvres routières typiques pouvait être effectivement approchée par analyse du comportement en régime stable.

Des essais routiers menés pour le compte du ministère des Transports de l'Ontario ont servi à valider les résultats de la modélisation, une bonne corrélation ayant pu être dégagée entre les deux groupes de résultats.

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Véhicule-citerne, stabilité des poids lourds, véhicule articulé, simulation informatique.	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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SUMMARY

In June 1985, S & S Inc. was contracted by the Transportation Development Centre to investigate the stability of heavy vehicles transporting liquid cargo. The study was initiated in view of the serious highway safety and environmental risks associated with rollover of tank vehicles, which contributes to the number of fatalities, personal injuries, and property damage losses in Canada.

The overall objective of this study was to improve the safety of highway freight vehicles transporting dangerous liquid cargo, through computer simulation and field testing. The project tasks included:

- Survey existing literature on liquid vehicle stability and tank design.
- Survey Canadian haulers and manufacturers to identify commonly used vehicle configurations.
- Review tank vehicle accidents to identify the dangerous occurrences associated with vehicle instabilities.
- Develop computer models to study the overturning limits of partially filled tank vehicles.
- Develop mathematical models to study the directional dynamics and stability of various tank vehicle configurations.
- Investigate stability limits of tank vehicles as functions of tank shape, percentage fill, and vehicle weights and dimensions.
- Conduct field tests to validate computer models.

In the study's initial phases, information related to vehicle rollover, tank vehicle configurations, and standards as well as practices associated with the transport of dangerous goods in Canada, U.S. and Europe was compiled. Haulers of fuel oils and chemicals, and tank manufacturers across Canada were surveyed to identify popular tank vehicle configurations and primary problems of concern. Canadian and U.S. highway accident files involving tank vehicles were reviewed to identify the major contributing factors. Results of the first phase revealed the following:

(a) Tractor-semitrailer (five- and six-axles) tank vehicles and B-trains (seven- and eight-axles) are the most popular configurations used to haul dangerous liquid goods across Canada.

(b) Cleanbore circular and compartmented modified-oval tanks are most commonly used in transportation of chemicals and fuel oils, respectively.

(c) Partial-fill condition occurs most frequently in general purpose chemical fleets.

(d) Vehicle rollover remains the primary problem of concern.

(e) Liquid slosh leading to lateral load transfer strongly contributes to vehicle instability.

Based on these findings, tractor-semitrailer and B-train combinations with either cleanbore or compartmented tanks of circular and modified-oval cross-sections were selected as candidate vehicles for further investigation.

Previous studies conducted in Canada, U.S., U.K., Sweden, and Australia, on stability of partially filled tank vehicles, were reviewed. From the literature review it was determined that most analytical models lacked comprehensive treatment of fluid slosh behaviour and its impact on vehicle stability.

Hence in this study, computer simulation software to investigate static and dynamic roll stability of tank vehicles was developed by employing a comprehensive dynamic fluid slosh model. The development of the computer simulation software was carried out in the following sequence:

(a) Develop a kineto-static vehicle model to establish rollover threshold limits of partially filled tank vehicles.

(b) Develop a three-dimensional tank vehicle dynamic model to investigate its directional behaviour.

(c) Develop a comprehensive dynamic fluid slosh model and investigate the stability limits, as influenced by the fluid slosh.

(d) Conduct field tests and validate computer models to investigate the directional dynamics of tank vehicles.

In the kineto-static vehicle model, a steady-state fluid slosh model of a partially filled tank was integrated with the roll plane model of the tank vehicle. Computer simulation was performed to study the influence of various tank design and operational factors. The following conclusions were drawn:

- Magnitude of lateral load transfer and associated overturning moment increases with reduced fill levels.
- Overturning limits of partially filled tank vehicles are considerably lower than those of equivalent rigid cargo vehicles.
- Lateral load shift within modified-oval and modified-square tanks is considerably larger than that in a circular tank. Tank vehicles with modified-oval and modified-square tanks therefore have lower overturning limits.
- Tank vehicles exhibit the lowest overturning limit at approximately 40% of fill level.
- Under constant axle loads, overturning limits of tank vehicles decrease with low fill level, while the overturning limits of corresponding equivalent rigid cargo vehicles increase.

- Modified-oval and -square tanks exhibit improved overturning limits while carrying lighter liquids, whereas circular tanks show better stability for denser liquids.

- Overturning limits of partially filled tank vehicles can be improved by using compartmented tanks.

A quasi-dynamic tank vehicle model was developed by integrating the steady-state fluid slosh model with a three-dimensional vehicle dynamics model. Computer simulation was performed to determine the directional performance and stability characteristics of tractor-semitrailer and B-train combinations equipped with circular and modified-oval cross section tanks. The directional response characteristics were evaluated for steady, as well as, realistic transient steering manoeuvres and compared to those of equivalent rigid cargo vehicles, in order to demonstrate the influence of liquid slosh behaviour.

Parametric sensitivity analyses were conducted to study the influence of fill level, axle load, and vehicle speed on the directional response of tank vehicle combinations. The following conclusions were drawn:

- Dynamic load transfer encountered during a constant steer manoeuvre yields unequal distribution of cornering forces between the two tracks, leading to considerable deviation in the path followed by a tank vehicle compared to that of an equivalent rigid cargo vehicle.

- Dynamic load transfer is strongly related to tank geometry, fill level, vehicle speed, and steer input.

- During a constant steer manoeuvre, an increase in vehicle speed from 60 km/h to 90 km/h leads to increased roll and lateral acceleration response of the five-axle tractor-tank-semitrailer and possible rollover, while the equivalent rigid cargo vehicle exhibits stable characteristics.

- A comparison of the dynamic characteristics of 5-axle and 6-axle tractor-semitrailer tank vehicles carrying maximum permissible load, reveals that 6-axle tank vehicles are considerably more stable than 5-axle tank-semitrailer vehicles.

- Partially filled tank vehicles and their equivalent rigid cargo vehicles exhibit stable behaviour during lane change manoeuvres, at typical highway speeds. Liquid cargo vehicles, however, exhibit larger roll and lateral acceleration.

- Partially filled tank vehicles are less stable than the equivalent rigid cargo vehicles in an evasive manoeuvre performed at highway speeds. The excessive load shift which occurs during evasive manoeuvres can lead to wheel lift-off and possible vehicle rollover.

- Roll angle and lateral acceleration amplification factors for a B-train tank vehicle are relatively large, indicating the likelihood of rear trailer rollover.

A comprehensive dynamic fluid slosh model was developed to investigate the influence of slosh forces and moments. The directional response characteristics of tank vehicles employing the dynamic liquid slosh model were compared to those of vehicles employing the quasi-dynamic model, in order to demonstrate the influence of dynamic slosh forces on vehicle stability.

Computer simulation of a tank vehicle employing the dynamic slosh model performed for a steady steer input indicates that the directional response oscillates at its fundamental mode of vibration around a mean value predicted by the quasi-dynamic model. Since typical steer frequencies lie well below the fundamental slosh frequency, simulation results reveal that the quasi-dynamic vehicle model can predict the directional response almost as accurately as the comprehensive dynamic fluid slosh model. The quasi-dynamic model, however, overestimates the response characteristics in the case of low frequency steer inputs, while good correlation is obtained for steer frequencies corresponding to typical highway manoeuvres.

The results of the computer simulation models were validated by comparing them to results obtained from field tests on a tank truck equipped with a cylindrical tank. Tests were conducted by the Ontario Ministry of Transport. Directional response characteristics were measured for typical right turn and lane change manoeuvres at various vehicle speeds and fill levels, and then compared with those obtained from the computer simulation. Results from the computer simulation correlated quite well with the field-measured results. This correlation provides the necessary confidence in computer models for predicting directional dynamics of tank vehicles.

Sommaire

En juin 1985, la firme S & S Inc. a reçu du Centre de développement des transports la tâche d'étudier en profondeur la stabilité des véhicules-citernes dans l'optique des grands dangers que fait courir à la sécurité routière et à l'environnement un accident par versement de ces poids lourds, et qui ajoutent au nombre de tués et de blessés sur les routes du Canada, ainsi qu'aux dégâts matériels.

L'objectif global fixé à l'étude a été d'améliorer la sécurité des poids lourds transportant des cargaisons liquides dangereuses, en faisant appel à la simulation assistée par ordinateur et à des essais routiers. Les tâches à effectuer étaient donc les suivantes:

- recherche documentaire sur le comportement des cargaisons liquides et sur la forme des citernes;
- enquête auprès des transporteurs et des fabricants canadiens sur les configurations les plus répandues dans ce secteur du transport;
- analyse des accidents impliquant des véhicules-citernes pour mettre en évidence ceux qui ont été le résultat d'une perte de stabilité;
- élaborer des modèles informatiques permettant d'approfondir les limites de stabilité transversale des véhicules-citernes transportant des charges partielles;
- élaborer des modèles mathématiques permettant d'étudier la directibilité et la tenue transversale des diverses configurations;
- approfondir les caractéristiques de stabilité transversale en fonction de facteurs tels que forme de la citerne, niveau de remplissage, poids et dimensions du camion-citerne;
- valider les modèles par des essais routiers.

La phase initiale de l'étude a porté: sur la compilation de données sur la stabilité transversale des diverses configurations utilisées, et sur les normes et les procédures adoptées pour le transport des marchandises dangereuses au Canada, aux Etats-Unis et en Europe; la conduite d'une enquête auprès des transporteurs routiers d'hydrocarbures et de produits chimiques et des constructeurs de citernes au Canada, pour connaître les configurations les plus demandées et mettre en évidence les principales causes d'instabilité; et enfin l'analyse des accidents routiers au Canada et aux Etats-Unis impliquant des véhicules-citernes, à la recherche des principaux facteurs contributifs. Cette étape a produit les résultats suivants:

a) les configurations les plus répandues au Canada pour le transport de cargaisons liquides dangereuses sont le tracteur/semi-remorque, à 5 ou 6 essieux (7 ou 8 essieux avec le train double du type B);

b) les citernes cylindriques sans cloisonnement et celles de forme ovale modifiée avec cloisonnement sont les plus répandues en transport de produits chimiques et d'hydrocarbures, respectivement;

c) les charges partielles sont surtout le fait des parcs roulants transportant des produits chimiques;

d) le versement constitue le problème majeur;

e) le ballottement de la cargaison aboutissant à un délestage latéral est un grand facteur d'instabilité.

A partir de ces constatations, le choix des configurations devant être étudiées s'est porté sur la citerne tractée avec et sans train double B, de forme cylindrique sans cloisonnement ou modifiée ovale avec cloisonnement.

Les chercheurs ont fait un tour d'horizon des recherches faites antérieurement au Canada, aux Etats-Unis, au Royaume-Uni, en Suède et en Australie dans le domaine de la stabilité des citernes à charges partielles; il en est ressorti qu'il manquait aux modèles analytiques une prise en compte globale du comportement en ballottement et, par conséquent, de son influence sur la tenue transversale.

Il a donc fallu étudier un modèle informatique de tenue transversale statique et dynamique, intégrant un modèle global de comportement dynamique en ballottement. Ce logiciel a été élaboré selon les étapes suivantes:

a) élaboration d'un modèle dynamique-statique permettant de définir les accélérations transversales limites dans le cas des véhicules-citernes à charges partielles;

b) élaboration d'un modèle dynamique tridimensionnel permettant d'étudier le comportement directionnel de ces véhicules;

c) mise au point du modèle de comportement dynamique en ballottement et recherche sur les limites de stabilité transversale en fonction de ce phénomène;

d) essais routiers, validation des modèles et recherche sur la stabilité directionnelle.

Le modèle dynamique-statique est le produit de l'intégration du modèle de comportement en régime stable d'une citerne partiellement remplie avec le modèle de tenue transversale dynamique. Ce modèle, qui a servi à mettre en évidence par simulation l'influence sur la stabilité de diverses formes de citernes et de divers facteurs d'exploitation, a abouti aux conclusions suivantes:

- l'amplitude des forces de balancement de la charge et du moment de versement qui en est la conséquence croit à mesure que les niveaux de remplissage décroissent;

- les accélérations transversales limites dans le cas des citernes partiellement remplies sont très inférieures à celles de véhicules témoins comparables transportant une cargaison rigide;

- le balancement de la charge à l'intérieur des citernes de forme ovale modifiée ou carrée est plus important qu'à l'intérieur de citernes cylindriques, d'où une réduction des accélérations transversales limites pour les premières;

- les accélérations transversales limites les plus basses correspondent aux citernes chargées à 40 p. 100 de leur capacité, environ;

- à charge à l'essieu invariable, les accélérations transversales limites des citernes diminuent lorsque le niveau de remplissage est faible, alors qu'ils augmentent dans le cas des véhicules témoins;

- les citernes de forme ovale modifiée ou carrée supportent des accélérations transversales plus élevées lorsqu'elles transportent des liquides à fluidité élevée, et les citernes cylindriques, lorsqu'elles transportent des liquides;

- le cloisonnement permet de relever les accélérations transversales limites des citernes partiellement remplies.

Un modèle de comportement quasi-dynamique a été obtenu par l'intégration du modèle du comportement en régime stable avec le modèle dynamique tridimensionnel. Ce modèle a permis de mettre en évidence les caractéristiques de directibilité et de stabilité de configurations tracteur / train double de type B / citerne cylindrique ou modifiée ovale. Les caractéristiques de directibilité ont été analysées tant en régime permanent qu'en régime transitoire (manoeuvres) et ensuite comparées à celles des véhicules témoins, de manière à faire ressortir l'influence du ballottement.

Les analyses paramétriques de sensibilité, faites à niveaux de remplissage, charges à l'essieu et vitesses de marche variées afin de faire ressortir leur influence sur la directibilité, ont mené aux conclusions suivantes:

- les efforts dus au balancement de la charge dans les virages à angle de braquage constant se traduisent par une répartition inégale des efforts de virage, ce qui entraine un écart marqué entre les trajectoires suivies par le tracteur et la citerne, comparativement à ce qui se passe avec le véhicule témoin;

- l'amplitude de ce balancement est fortement influencé par la forme de la citerne, le niveau de remplissage et l'angle de braquage;

- dans les virages à angle de braquage constant, le passage de 60 à 90 km/h se traduit par un accroissement des forces d'accélération latérale et des moments de roulis dans le cas d'un camion-citerne à 5 essieux et par la possibilité d'un versement, alors que, pour le véhicule témoin, ces caractéristiques sont inchangées;

- il a été établi que les caractéristiques de stabilité dynamique d'un ensemble tracteur / semi-remorque-citerne à 6 essieux sont de loin meilleures que celle d'un ensemble correspondant à 5 essieux, chacun au poids total en charge maximum admissible;

- les véhicules-citernes partiellement remplis et les véhicules témoins ont un comportement stable durant les changements de file aux vitesses normalement pratiquées. Mais les accélérations latérales créées et les moments de roulis sont plus élevées dans le cas des véhicules-citernes.

- dans les manoeuvres d'évitement aux vitesses normalement pratiquées, les véhicules-citernes partiellement remplis sont moins stables que les véhicules témoins, et des efforts de balancement excessifs

peuvent mener à un éventuel délestage des roues et au versement du véhicule;

- les facteurs d'amplification des forces d'accélération latérale et des moments de roulis dans le cas d'un véhicule-citerne avec train double de type B sont relativement importants, d'où le risque possible du basculement de la citerne arrière.

Un modèle global de comportement dynamique en ballottement a été élaboré, permettant d'analyser l'influence des forces et des moments créés par le ballottement. Les résultats fournis par ce modèle en ce qui concerne la directibilité des véhicules-citernes ont été comparés à ceux fournis par le modèle de comportement quasi-dynamique dans le but de mettre en évidence l'influence des forces de ballottement sur la stabilité directionnelle.

La simulation du comportement d'un véhicule-citerne à l'aide du modèle de comportement dynamique en ballottement et dans des virages à angle de braquage constant a montré que la réponse directionnelle fluctue à sa fréquence vibratoire propre autour d'une valeur moyenne décrite par le modèle quasi-dynamique. Etant donné que les fréquences vibratoires durant les virages se situent bien au-dessous de la fréquence propre en ballottement, les résultats portent à croire que les prévisions sur la réponse directionnelle fournies par le modèle quasi-dynamique sont aussi fidèles que celles du modèle de comportement dynamique, plus global. Le premier a tendance à surévaluer cette réponse lorsque les fréquences vibratoires durant les virages sont faibles, mais lorsque ces fréquences correspondent aux valeurs types pour les manoeuvres normalement pratiquées, il dégage une bonne corrélation.

Des essais routiers avec une citerne cylindrique ont servi à valider les résultats de la modélisation. Menés pour le compte du ministère des Transports de l'Ontario, ils ont comporté divers types de changements de direction. La réponse directionnelle a été mesurée à l'égard d'un virage normal à droite et d'un changement de file, à des vitesses et des niveaux de remplissage variés, et ensuite comparée à celle fournie par la modélisation. La corrélation dégagée ayant été bonne, il devient désormais possible de faire confiance à la modélisation pour la prévision de la stabilité dynamique des véhicules-citernes.

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1. STABILITY OF TANK VEHICLES - AN OVERVIEW

Cargo tank trucks are the prime movers of dangerous goods on our highways. Safe transportation of such hazardous products in highway tank trucks deals with factors other than normal trucking practices, such as loading and unloading procedures, structural integrity to withstand stresses due to liquid surge, containability in the event of an accident, and stability and controllability of the vehicle influenced by the mobility of liquid cargo within a partially filled tank [1].

For reasons of economy, the trucking industry has been inclined towards increasing sizes and load carrying capacities of heavy freight vehicles. Further, during the past few years, vehicle weights and dimensions regulations have been relaxed in Canada. Increased vehicle weights and dimensions adversely influence handling and manoeuvrability characteristics of these vehicles [2]. The rollover immunity and directional stability limits of articulated tank vehicles are quite low, not only due to increased weights and dimensions, but also due to dynamic interactions of the sloshing cargo. Operational safety of partially filled tank vehicles is thus adversely influenced by the dynamic movements of the liquid cargo.

1.1 Tank Vehicle Accidents

Highway accidents involving tank vehicles transporting dangerous liquid cargo pose high risks to environment, health and safety of the general population, and commercial property. In view of an increased tank vehicle population on Canadian highways, the operational safety of such vehicles has drawn considerable attention from industry and various levels of Government. It is, therefore, vital to investigate the potential hazards and safety limits of such vehicles. This necessitates critical examination of the past accident history in order to identify the problems and to propose better operating practices that can reduce the magnitude of potential environmental hazards, loss of human life, and property damages. In the U.S., significant attempts have been made to collect data pertaining to accidents involving tank vehicles carrying hazardous materials. The collected accident data were analyzed in order to revise the regulations (49 CFR 171.8) [3] so as to ensure safe transportation of hazardous materials. In Canada, there have been problems associated with collection of data on dangerous occurrences due to absence of a centralized accident reporting and data collection mechanism [4].

A dangerous occurrence, by definition, is a transportation incident leading to discharge, emission or escape of dangerous goods, or an emission of radiation exceeding permissible levels. Accidents during loading, unloading and temporary storage are also considered to be reportable dangerous occurrences. The compiled data on dangerous occurrences is far from comprehensive, and is not considered to be representative for road transportation, because of inconsistent reporting and varying standards between responsible Governmental jurisdictions. In addition, the accident reports on file provide only limited information on the cause of the accident. An analysis of dangerous occurrences reported in Canada, during 1981-83, clearly revealed that the road mode of transportation accounted for a majority of the dangerous occurrences, as illustrated in Table 1.1 [4,5]. 56% of the total number of reportable occurrences, during 1981-83, occurred in transit,

while 34% occurred during storage and handling. Information pertaining to the accident phase was unavailable for the remaining 10% of the dangerous occurrences.

TABLE 1.1
DANGEROUS OCCURRENCES IN TRANSIT DURING 1981-83 [4,5]

MODE OF TRANSPORT	% OF DANGEROUS OCCURRENCES
ROAD	76
RAIL	18
AIR	2
MARINE	4

Dangerous goods are classified by nine classes as defined under the Transportation of Dangerous Goods Act. Of these, flammable liquids and fuel oils grouped under Class 3, have the highest frequency of involvement in dangerous occurrences as illustrated in Table 1.2. An analysis of dangerous occurrences involving Class 3 goods revealed that 70% of the accidents occurred in the road mode and 14% in the rail mode of transportation.

The available data on tank vehicle accidents in Canada, during 1981-83, have been reviewed to establish the primary and secondary causal factors. The most probable factors, associated with dangerous occurrences in the road mode are listed in Table 1.3 [4,5]. Unfortunately, reporting mechanisms fail to account for the causal factors, such as longitudinal fluid surge during sudden braking and lateral surge of the fluid during directional manoeuvres at highway speeds. Although the majority of the accidents have been attributed to human factors, the influence of longitudinal and lateral slosh has been emphasized only in a limited number of accident reports [5].

The tank vehicle accidents data are classified into two categories: single vehicle and multi-vehicle accidents. A total of 85 accident reports involving tank vehicles are reviewed, in which 59 reports deal with single vehicle accidents, and the rest involved multiple vehicles [5]. A review and analysis of the single vehicle accident reports concluded that human factors are the primary cause of vehicle accidents. However, various other contributing factors, such as lateral liquid surge, instability during braking on a downgrade and driver's unfamiliarity with the road have also been identified. Review of the accident reports also revealed that most of the accidents occurred while negotiating a curve. This may be due to the excessive liquid surge occurring during simultaneous curving and braking of the vehicle. Multi-vehicle accidents, similar to single vehicle accidents, revealed human factors as the primary cause of accidents.

TABLE 1.2
DANGEROUS OCCURRENCES DURING 1981-83 BY CLASS OF DANGEROUS GOODS [4,5]

CLASS OF DANGEROUS GOODS	% OF DANGEROUS OCCURRENCES*
1	0.3
2	11
3	58
4	3
5	3
6	8
7	0.1
8	11
9	3
UNKNOWN	3

* Percentage may not add to 100% due to rounding off.

TABLE 1.3
CAUSAL FACTORS RELATED TO DANGEROUS OCCURRENCES [4,5]

Causal Factors	NATURE OF OCCURRENCE (%)*		
	Vehicle Overturn	Collision with other Vehicles	Handling
Human Factors	85	67	100
Weather Conditions	6	5	-
Poor Roads	4	-	-
Equipment Failure	2	2	-
Human Error	-	13	-
Unknown	2	13	-

* Percentage may not add up to 100%, due to round off.

1.2 Tank Design Factors and Vehicle Stability

General design standards and safety regulations for vehicles carrying dangerous goods in Canada have been outlined by the CSA *(Canadian Standards Association)* B338-1982 [6]. This standard applies to highway tanks used for transportation of dangerous goods by road mode and portable tanks used for transportation of dangerous goods through other modes. The standard describes the design, construction, testing, inspection and re-testing, maintenance, and identification aspects of such tanks. Highway tanks are designated as TC 306, TC 307, TC 312, or TC 331. TC 306 tanks are generally used to haul petroleum products, while the majority of the chemicals are hauled by TC 307 and TC 312 tanks. TC 331 tanks are used to haul compressed gases at high pressures such as anhydrous ammonia and propane.

Figure 1.1 illustrates the summary of dangerous occurrences involving MC 306, 307 and 312 tank trucks in U.S., during 1983-87 [7]. Large spills refer to spills over 100 gallons. The figure clearly demonstrates that MC 307/312 outperforms the MC 306. The study further revealed that vehicle rollover remains the primary cause of concern and major focus for research. The TAF (*Traffic Accident Files*) database, maintained by the BMCS (*Bureau of Motor Carrier Safety*), indicates 2872 rollovers per year (based upon 33,700 reported accidents) in non-collision accidents. No data is, however, collected on rollovers in collision accidents. It has been reported that the TAF database lacks a large number of accident reports involving rollovers and cargo spills.

The NASS (*National Accident Sampling System*) database, maintained by NHTSA (*National Highway Traffic Safety Administration*) of DOT (*Department of Transportation*) reported as many as 15,800 rollovers based upon 181,000 accidents per year. The rollover frequency, as listed by the BMCS and NASS databases, is presented in Figure 1.2.

Some of the general design and construction requirements applicable to TC 306, TC 307, and TC 312 cargo tanks include:

(a) Construction Practices: The general construction practices for cleanbore and compartmented tanks are listed in section 173 of the U.S. DOT code [3].

(b) Material: All sheet and plate materials required for shell, heads, bulkheads and baffles are specified as per *ASME Boiler and Pressure Vessel's Code*. Additional material requirements, however, apply to those parts which are exempted from the above code.

(c) Structural Integrity: Maximum calculated stress must be less than 20% of the minimum ultimate strength except when ASME code for pressure vessel design requirements apply. Additional structural integrity is necessary for cases where applicable, such as change in dynamic loading, internal pressure, and temperature gradient.

The standard also addresses the design requirements for joints, supports, circumferential reinforcements, and accident damage protection.

Bulk liquid goods represent a broad range of densities, viscosities and

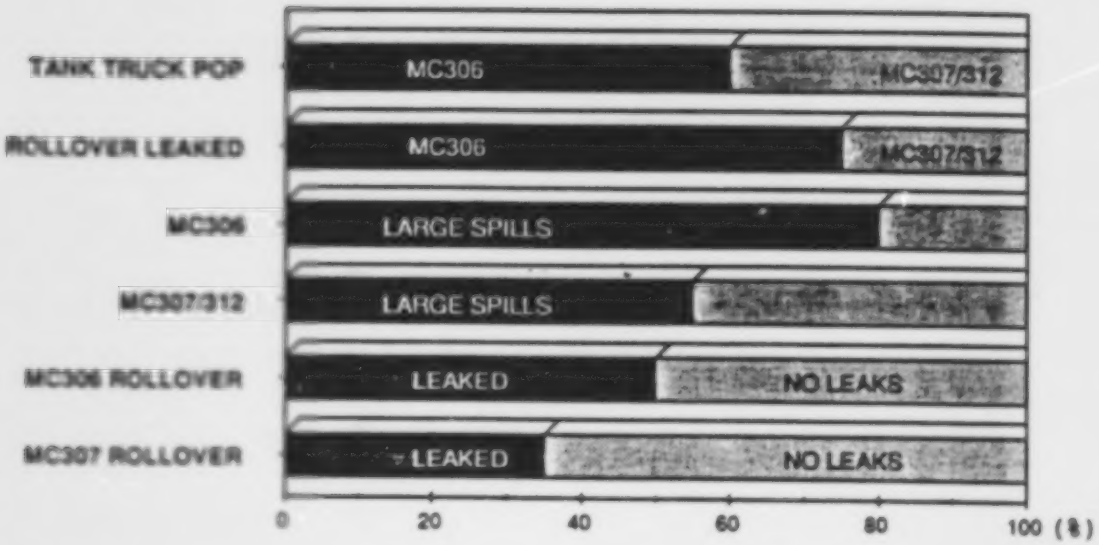


Figure 1.1: Comparison of dangerous occurrences involving MC306, MC307 and MC312 tank trucks [6].

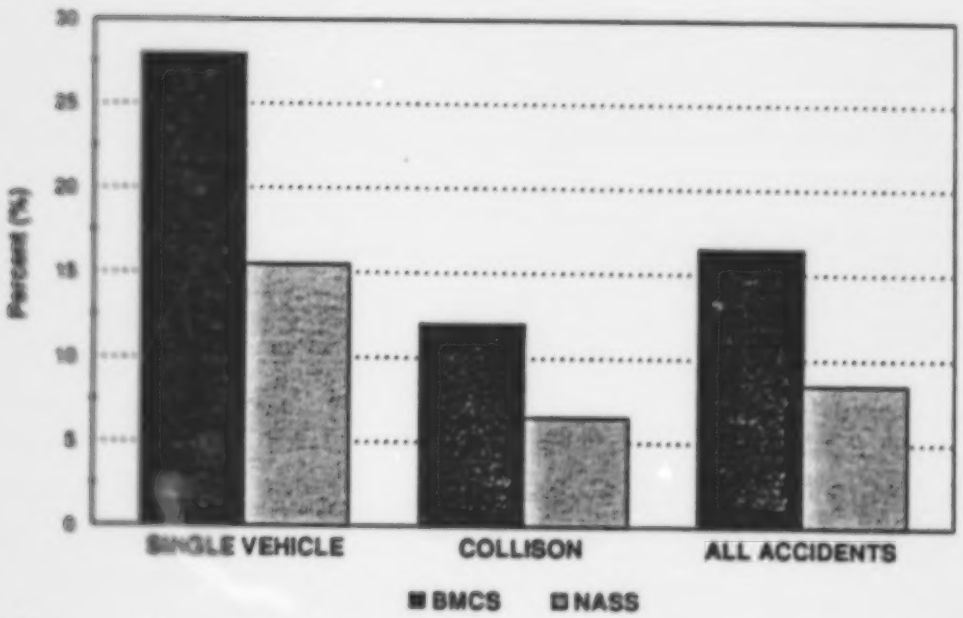


Figure 1.2: Tank vehicle rollovers indicated by BMCS and NASS [6].

chemical properties. A recognition of various groups of liquid cargo is necessary, since different types of equipment are generally chosen for safe and economical transportation of different chemicals. Tanks and their handling equipment are primarily designed for the following three groups of cargo, based upon their weight densities and chemical properties.

(a) Fuel oils such as gasoline, diesel oil, and domestic fuel oil.

(b) Industrial acids.

(c) Highly viscous petrochemical, and asphalt products.

In view of the demand for transportation of various types of chemicals, haulers and tank manufacturers have been concentrating on tank designs which will provide the versatility needed to accommodate a broad variety of haulable products. Although tanks of varying shapes and cross-sections have been designed, the straight-circular cleanbore tanker has been the most popular one for general purpose chemical fleets. Since baffles increase the weight and cost, reduce payload capacity, and interfere with cleaning, general purpose chemical tanks are designed with no baffles. Although baffles within a tank do not affect the lateral slosh forces and thus the lateral stability of the vehicle, baffles can offer resistance to longitudinal slosh forces arising during acceleration and deceleration [8].

Tanks are often designed with compartments to permit hauling of different products, and handling of various sizes of shipments, as well as to meet different road laws. Compartments within a tank can further eliminate partial fill condition and thus minimize the magnitude of slosh forces.

1.3 Dynamics of Tank Vehicles - Literature Review

The dynamic interactions associated with movement of liquid cargo within a partially filled tank vehicle adversely affect the control and handling characteristics. The rollover immunity levels of heavy commercial vehicles are known to be so low that a moderately severe manoeuvre can cause considerable lateral forces and roll moments leading to vehicle rollover [9]. Rollover immunity and stability of tank vehicles are further diminished due to sloshing of liquid cargo. The degradation of rollover immunity of tank vehicles is primarily attributed to the motion of the free surface of liquid within a partially filled tank. Liquid tank vehicles, employed in general purpose chemical transportation, are often partially filled to meet the regulatory limitations on axle loads, while carrying chemicals of varying weight density. Movement of the free surface of liquid within a partially filled tank coupled with the dynamics of the vehicle system yield significant slosh forces. The longitudinal and lateral slosh forces caused by abrupt vehicle manoeuvres can adversely affect the controllability and stability of a tank vehicle [10].

Typical highway freight vehicles exhibit roll instability near 0.34 g (rollover threshold), while a 50%-filled elliptic tank vehicle can rollover at a lateral acceleration of 0.20 g during a lane change manoeuvre [11]. Although extensive analytical and experimental studies have been reported on directional dynamics and stability of heavy vehicles carrying rigid cargo [12-18], only a limited number of studies have been reported on dynamics of

tank vehicles. Isermann [19] was the first to develop a roll plane model of an articulated vehicle carrying rigid or liquid loads. Sensitivity of the vehicle's rollover threshold to design and loading parameters was investigated using the roll plane model. The lateral load shift due to movement of liquid cargo in a partially filled tank trailer, however, was neglected in the analysis.

An analytical model, capable of simulating dynamic response of tractor-semitrailers and double trailers to various types of steer inputs, was developed by Strandberg *et al* [20, 21]. The model has been used to evaluate vehicle response to specified directional manoeuvres and to establish performance standards in Sweden. The assumption of small roll angles, however, did not permit simulation of vehicle rollover.

Study of liquid slosh within a moving container involves complex modeling and analysis. Slibar and Troger [22] developed an equivalent single-degree-of-freedom mechanical oscillator to simulate the liquid slosh forces within a tank vehicle. The dynamic liquid slosh is represented by an oscillating mass elastically coupled to another fixed mass. The equivalent mass and spring constant for the oscillating liquid was derived from field test data. Abramson [23] developed a pendulum analogy model to study liquid slosh forces in the fuel tank of a spacecraft.

The references cited above indicate that analytical models for directional dynamics of articulated tank vehicles lack either comprehensive modeling of liquid slosh behaviour or a comprehensive vehicle model.

2. OBJECTIVES OF THE STUDY

The overall objective of the study is to contribute to the attainment of improved safety of highway tank vehicles through systematic development of methodologies, software, computer simulation and interpretations. The project objectives include: (i) literature review and survey of haulers and manufacturers to identify the problems; (ii) development of analytical models of tank vehicles to investigate their stability and manoeuvrability limits; and (iii) stability analysis of candidate tank vehicle configurations. The study is conducted in five sequential phases. Objectives of each phase of the study are listed below.

Phase I: Conduct a review of accident files, and survey haulers and manufacturers with following objectives:

(i) Identify the problems of primary concern.

(ii) Select candidate tank vehicle configurations.

(iii) Select candidate tank cross-sections.

Results of this initial phase of study have been reported in the interim report [5], and further summarized in section 1 of this report.

Phase II: Develop a kineto-static vehicle model to establish rollover threshold limits of partially filled tank vehicles.

The results of this phase of investigation have been reported in the interim report [24], and further summarized in sections 1 and 4.

Phase III: Develop a comprehensive tank vehicle dynamic model to investigate its directional behaviour. The objectives of this phase of investigation include:

(i) Develop a quasi-dynamic model of a partially filled tank.

(ii) Integrate the steady-state fluid slosh model with the vehicle dynamics model representing the roll and lateral behaviour.

(iii) Evaluate directional response characteristics of tank vehicles as a function of vehicle configuration, fill level, and tank cross-section.

(iv) Establish stability limits of liquid tank vehicles in relation to those of the rigid cargo vehicles.

(v) Evaluate directional dynamics of tank vehicles subjected to transient steering manoeuvres.

(vi) Evaluate the stability limits of compartmented tank vehicles.

Partial results of this phase of investigation have been reported in the interim report [25], and further presented in section 5 of this report.

Phase IV: Develop a comprehensive transient fluid slosh model and investigate the stability limits, as influenced by the fluid slosh.

The primary objectives of this phase of the study are:

(i) To determine the influence of steering frequency on fluid slosh.

(ii) To compare the vehicle dynamics models with steady-state and transient fluid slosh representation in predicting the directional behaviour.

Phase V: Conduct field tests and validate the computer model developed to investigate the directional dynamics of tank vehicles.

3. TANK VEHICLE CONFIGURATIONS

A large number of commercial vehicle configurations, such as straight trucks, tractor-semitrailers, truck-trailers, B-trains, etc. are used in general purpose transportation of liquid bulk across Canada. Dynamic characteristics of selected candidate tank vehicle configurations were investigated. Candidate tank vehicle configurations were selected based on the surveys conducted by RTAC/UMTRI [26] and CONCAVE [24], and discussions with the steering committee of this contract.

3.1 Selection of Candidate Tank Vehicle Configurations

Table 3.1 presents the percentage population of various vehicle combinations currently in use across Canada. According to research conducted by the University of Michigan Transportation Research Institute (UMTRI), approximately 77% of all heavy vehicles operating in Canada are tractor-semitrailers, 17% are A-doubles, 5% are B-doubles, and remaining are C-doubles and triples [26]. A survey of haulers of tank vehicles and tank manufacturers across Canada was conducted to determine the tank vehicle configurations used most frequently for transportation of bulk liquids [24]. The results of the survey are summarized in Table 3.2. The findings of the UMTRI and the bulk liquid carriers survey revealed that a vehicle configuration consisting of a tractor with tandem, tri- and quad-axle semitrailer is most often used on Canadian highways. The second most popular vehicle configuration used in transportation of gasoline and fuel oils, is either a 7-axle or 8-axle B-train combination. Thus, tractor-semitrailer and B-train configurations were selected as the candidate vehicles for this investigation. Figure 3.1 presents a schematic of the candidate vehicle configurations.

3.2 Selection of Tank Cross-Sections

Tanks of various cross-sections have been designed for bulk transportation of gasoline and chemicals. Of these, tanks with circular, modified-oval, elliptical and modified-square cross-sections are widely used in transportation of gasoline, fuel oils, and chemicals. Figure 3.2 presents typical cross-sections of some of the tanks used in the industry. The liquid load shift within a tank vehicle and the height of the sprung weight centre of gravity are strongly dependent on the tank cross-section and fill level. Hence, the overturning threshold limits of tank vehicles will be influenced by the choice of tank cross-section. Although a rectangular cross-section tank can provide least overall height of the vehicle, for a given cross-sectional area and payload, the sharp corners can impose high stresses in the tank walls. Bends of small radius are introduced to join the various arcs to improve the structural integrity of the tank. The results of the survey conducted on the bulk carriers [24] revealed that tanks of circular and modified-oval cross-section are most commonly used for transportation of chemicals and fuel oils.

TABLE 3.1
POPULATION OF VARIOUS HEAVY VEHICLE COMBINATIONS PRESENT IN VARIOUS CENTRES ACROSS CANADA [26]

Vehicle Combination	% Distribution of Vehicle Combination					
	Vancouver	Calgary	Winnipeg	Toronto	Montreal	Moncton
Tractor-Semitrailers	60	80	60	70	90	98
A-Doubles	32	8	25	25	8	1
B-Doubles	8	10	14	5	2	1
C-Doubles	0	<2	<1	<1	<1	0
Triples	0	<1	<1	0	<1	0
Total	100	100	100	100	100	100

TABLE 3.2
MOST COMMONLY USED TANK VEHICLE CONFIGURATIONS IN CANADA [24]

CARRIER	VEHICLE CONFIGURATIONS
Shell Canada	7-axle B-train
Provost Inc.	Tandem Semitrailer Triaxle Semitrailer
Canadian Liquid-Air Ltd.	C-train Triaxle Semitrailer
Fruehauf Inc.	Tandem Semitrailer Triaxle Semitrailer 8-axle B-train
Bulk Carriers Ltd.	Tandem Semitrailer Triaxle Semitrailer Quadaxle Semitrailer
Westank Ltd.	B-train A-train
Hutchinson Inc.	Tandem Semitrailer Triaxle Semitrailer
Gulf Canada	8-axle B-train Triaxle Semitrailer
Trimac Inc.	8-axle B-train Quadaxle Semitrailer
Remtec Inc.	7-axle B-train 8-axle B-train Triaxle Semitrailer

TRACTOR-SEMITRAILER

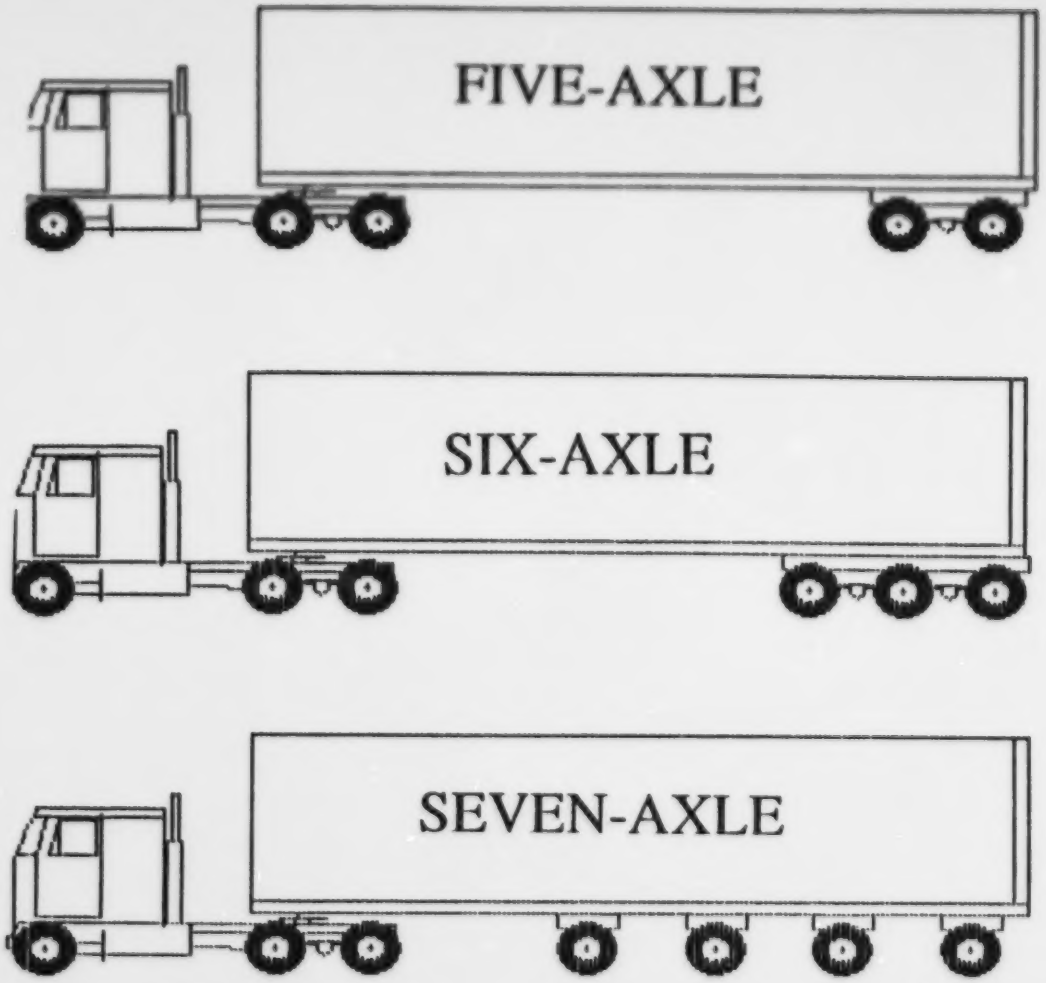


Figure 3.1: Schematics of Candidate Vehicle Configurations (continued)

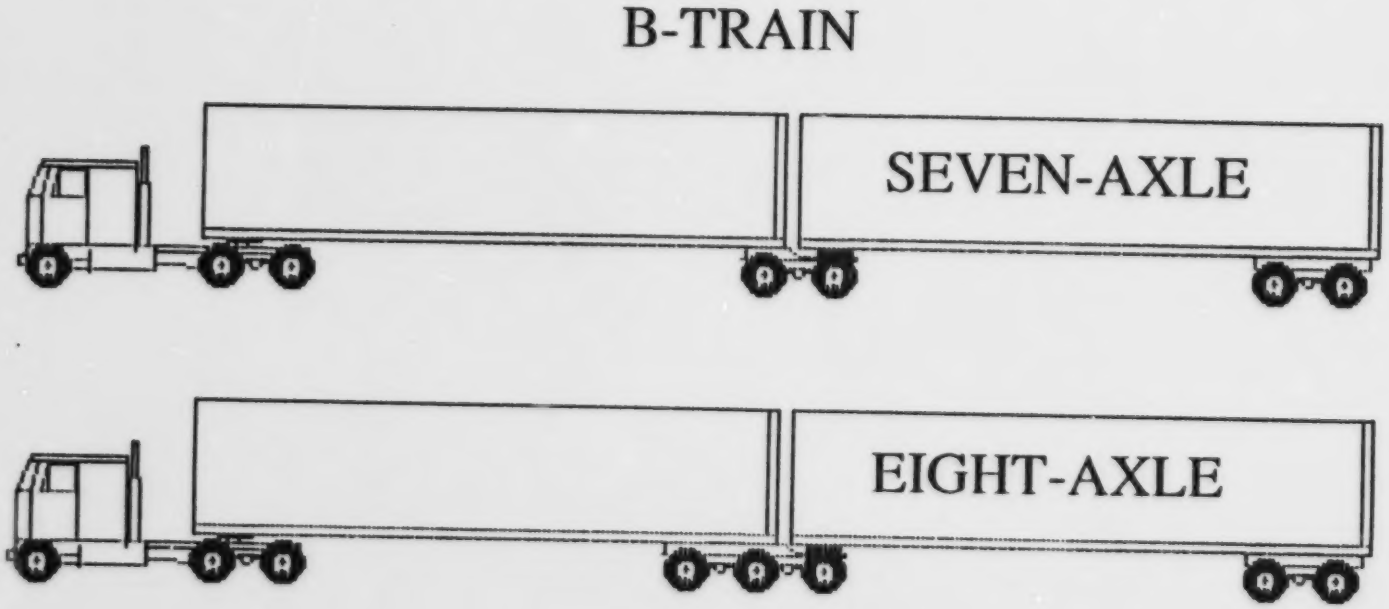


Figure 3.1: Schematics of Candidate Vehicle Configurations.

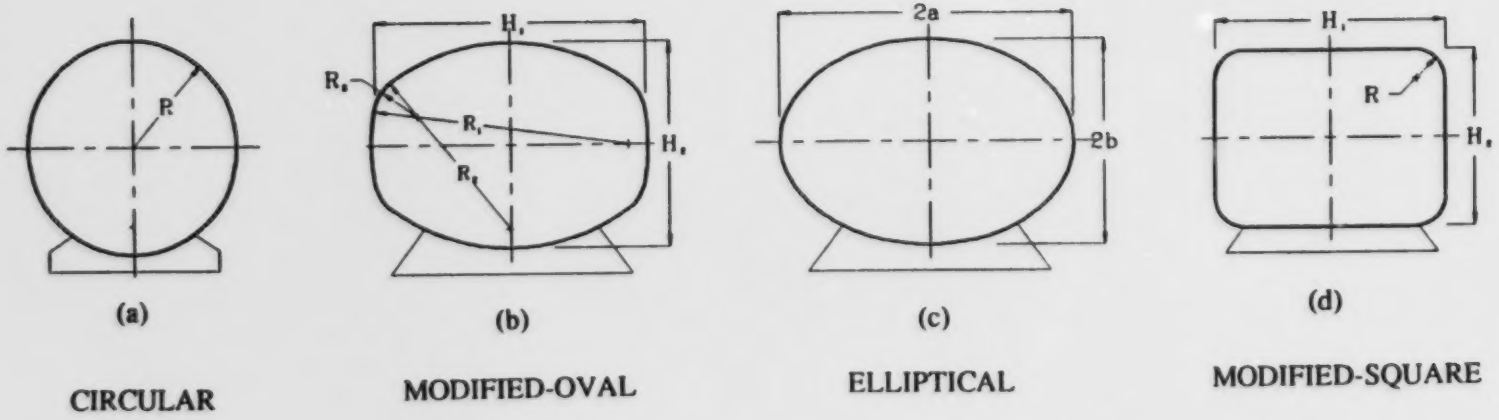


Figure 3.2: Schematic of Candidate tank cross-sections.

4. STEADY TURNING STABILITY OF TANK VEHICLES

Heavy vehicles, in general, begin to exhibit unstable behaviour at lateral acceleration levels of 0.3 to 0.4 g. The likelihood that a certain vehicle manoeuvre can lead to vehicle rollover is strongly related to rollover threshold acceleration of the vehicle in steady turning. A steady turning model is thus developed to determine the rollover threshold of partially filled tank vehicles. The steady turning model of a tank vehicle is developed by integrating a steady-state model of the fluid slosh within the tank to the kineto-static roll plane model of the tank vehicle.

4.1 Steady-State Fluid Slosh Model of a Partially Filled Tank

The magnitude of liquid motion within a tank depends upon the tank cross-section, and hence, the rollover immunity level of the vehicle is significantly affected by the tank geometry. The sprung and unsprung masses of an articulated vehicle experience roll as well as lateral (centrifugal) acceleration during a steady turning manoeuvre. Assuming steady-state conditions, vehicle roll causes the motion of the free surface of the liquid as shown in Figure 4.1. The centre of mass of liquid experiences a shift due to motion of the free surface of liquid causing a load transfer from the inner to the outer tires. The lateral acceleration experienced by the sprung mass of the vehicle during the manoeuvre imposes an equal and opposite acceleration on the liquid bulk resulting in further motion of the free surface of liquid and the centre of mass of liquid as shown in Figure 4.2.

The translation of the centre of mass of liquid bulk due to motion of the free surface leads to considerable load shift from the inner to outer track of the vehicle. The magnitude of translation of the centre of mass is a function of tank cross-section, fill level, and gradient of the free surface due to tank roll and lateral acceleration. Assuming inviscid fluid motion, the gradient of free surface of liquid is given by [24]:

$$\tan \phi = \frac{\theta_{s3} - a_y}{(1 + a_y \theta_{s3})} \qquad (4.1)$$

Where a_y is lateral acceleration of the vehicle, θ_{s3} is roll angle of the trailer's sprung mass and ϕ is gradient of the free surface of liquid. Translation of the centre of mass of liquid bulk in a partially filled tank and the corresponding lateral load shift can be then computed from the gradient of free surface, tank cross-section, and fill level.

4.1.1 CIRCULAR CROSS-SECTION TANK

Figure 4.3 illustrates the roll plane steady-state fluid slosh model of a partially filled circular tank. Although, circular tanks are normally cleanbore, the analysis presented here is applicable to both cleanbore as well as compartmented tanks. The lateral and vertical translation of the centre of mass of liquid within a compartment are then computed from following equations, derived from tank geometry [24]:

a - C.G. of solid load
b - C.G. due to tank tilt alone
c - C.G. due to tank tilt and lateral acceleration

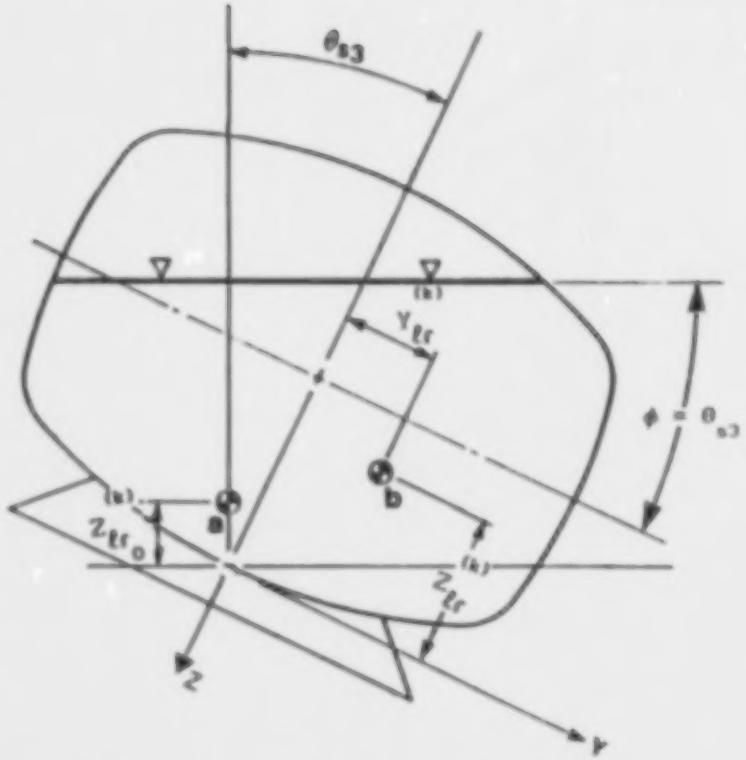


Figure 4.1: Translation of Centre of Gravity (C.G) of liquid due to tank tilt.

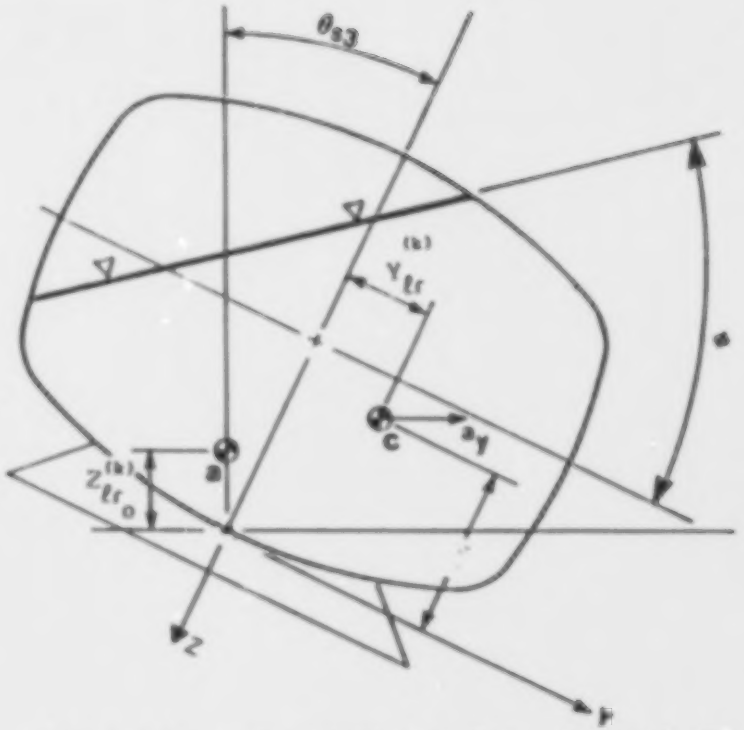


Figure 4.2: Translation of C.G. of liquid due to tank tilt and lateral acceleration.

a - C.G of solid load
b - C.G due to tank tilt alone
c - C.G due to tank tilt and lateral acceleration

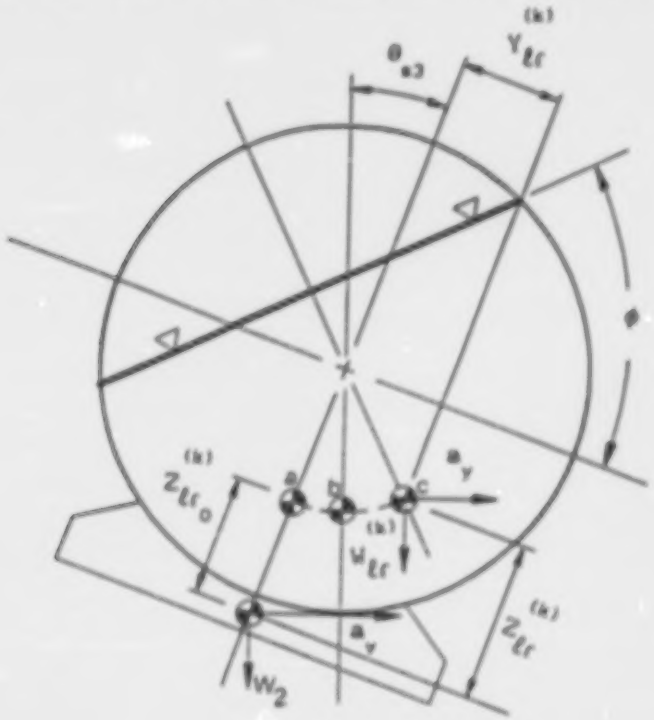


Figure 4.3: Roll plane steady state fluid model of a partially filled circular tank cross-section.

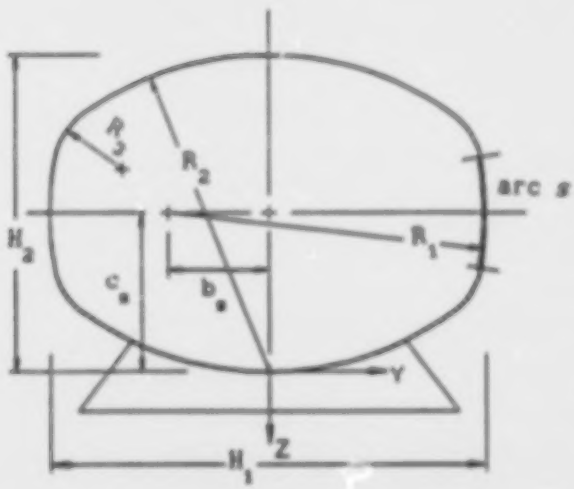


Figure 4.4: Cross-section of a Modified-Oval tank.

$$Z_{tf}^{(k)} = R - \left(R - Z_{tf_0}^{(k)}\right) \cos\phi \quad ; \quad k = 1,2,\ldots,n \tag{4.2}$$

$$Y_{tf}^{(k)} = \left(R - Z_{tf_0}^{(k)}\right) \sin\phi \quad ; \quad k = 1,2,\ldots,n \tag{4.3}$$

where R is tank radius, n is number of compartments (for a cleanbore tank, $n = 1$), $Z_{tf_0}^{(k)}$ is vertical coordinate of centre of mass of liquid in compartment k in the absence of roll and lateral acceleration ($\theta_{s2} = 0$ and $a_y = 0$), and $Z_{tf}^{(k)}$ and $Y_{tf}^{(k)}$, respectively, are the vertical and lateral locations of the centre of mass of liquid in compartment k, due to tank roll and lateral acceleration encountered during steady turning.

4.1.2 MODIFIED-OVAL CROSS-SECTION TANK

Figure 4.4 illustrates the cross-section of a modified-oval tank of width H_1 and height H_2, enclosed by circular arcs of radii R_1, R_2, and R_3. The tank periphery can be observed as a combination of 8 circular arcs and is symmetric about the vertical axis. An iterative numerical algorithm is developed to compute the magnitude of lateral and vertical translation of centre of mass of fluid within the tank [24].

4.1.3 MODIFIED-SQUARE AND ELLIPTIC CROSS-SECTION TANKS

Modified-square cross-section, as shown in Figure 3.2 (d), can be realized from a modified-oval cross-section by selecting large values of R_1 and R_2. Hence, the iterative algorithm developed for a modified-oval cross-section tank can also be used to compute the lateral and vertical translation of centre of mass of liquid within a modified-square tank cross-section. The magnitude of vertical and lateral translation of centre of mass of liquid within an elliptic tank can also be computed using the same algorithm.

4.2 Kineto-Static Roll Plane Model of an Articulated Tank Vehicle

An articulated vehicle with multiple axles and a compartmented tank of arbitrary cross-section is considered to study the steady turning rollover threshold of the vehicle. The multi-axled vehicle is represented by three composite axles by grouping axles with similar suspension properties. The sprung weight of the tractor is represented by two sprung weights, W_f and W_r, supported by front and rear composite axles of the tractor, respectively. The two sprung weights are coupled through the torsional compliance of the tractor frame, as shown in Figure 4.5. The torsional compliance of the tractor frame is represented by a torsional spring element, K_{tf}, and coulomb friction, C_{tf}

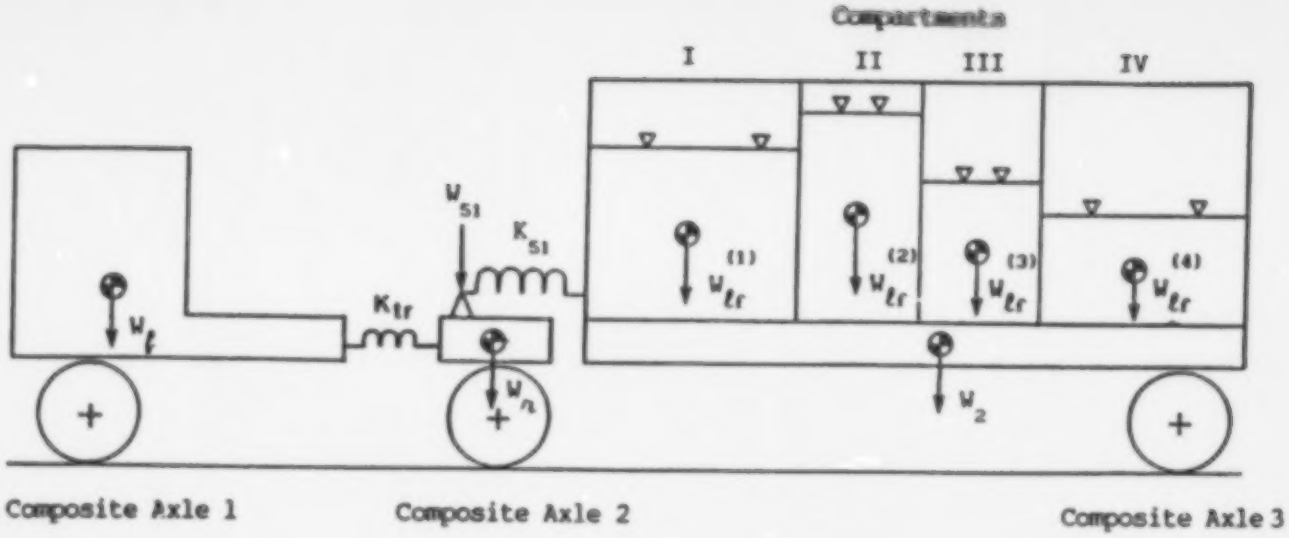


Figure 4.5: Representation of the tractor-tank semitrailer and the axles.

The trailer sprung weight is represented by $(n+1)$ sprung weights: sprunweight of the tank-semitrailer structure, W_2, and n sprung weights, $W_{\ell f}^{(k)}$, $k = 1,2,..,n$, due to liquid cargo in n compartments. The sprung weight due to tank-semitrailer is coupled to the tractor sprung weight, W_1, through torsional compliance of the fifth wheel and tank-trailer structure, K_{s1}, as shown in Figure 4.5. The kineto-static roll plane model of the tank vehicle is developed by integrating the roll plane steady-state fluid slosh model of the tank and the roll plane model of the articulated vehicle as shown in Figure 4.6. It should be noted, that coordinates of the centre of mass of liquid in compartment k are represented by $(Y_{\ell f}^{(k)}, Z_{\ell f}^{(k)})$ with respect to the fixed sprung mass centre of the tank-semitrailer structure.

Simplifying assumptions made during development of the kineto-static roll plane model of the tank vehicle are summarized as follows:

(i) The sprung weights are assumed to rotate about their respective roll centres which are located at a fixed distance from their centre of mass.

(ii) The suspension springs are considered to deflect along the vertical direction parallel to the vertical axis of the unsprung mass, k_{ui}.

(iii) The suspension non-linearities such as backlash, interleaf friction and progressively hardening characteristics are incorporated through a tabular input and linearized about the operating point during simulation.

(iv) The lateral and vertical stiffness of the tires (KY_{ij} and KT_{ij}, where i represents the composite axle and j represents the number of tires on each composite axle, respectively) are assumed to be linear.

(v) At lateral accelerations close to the rollover limit of the vehicle, load transfer to the tires located on outside of the turn is quite significant. Thus, the lateral forces developed by tires on the inside of the turn are assumed to be negligible.

(vi) The roll resisting moments developed due to camber are represented through torsional springs, $KOVT_{ij}$, located at tire/road interface.

(vii) The relative motions between sprung and unsprung weights are assumed to occur about the roll centres.

(viii) Roll angles are assumed to be small for both sprung and unsprung masses, such that $\sin\theta \approx \theta$ and $\cos\theta \approx 1$.

(ix) The influence of articulation on roll response of the tank vehicle is neglected while assuming small articulation angles. The sprung weights at various axles experience different vertical deflections. Thus vehicle pitching during rollover can be incorporated in the model.

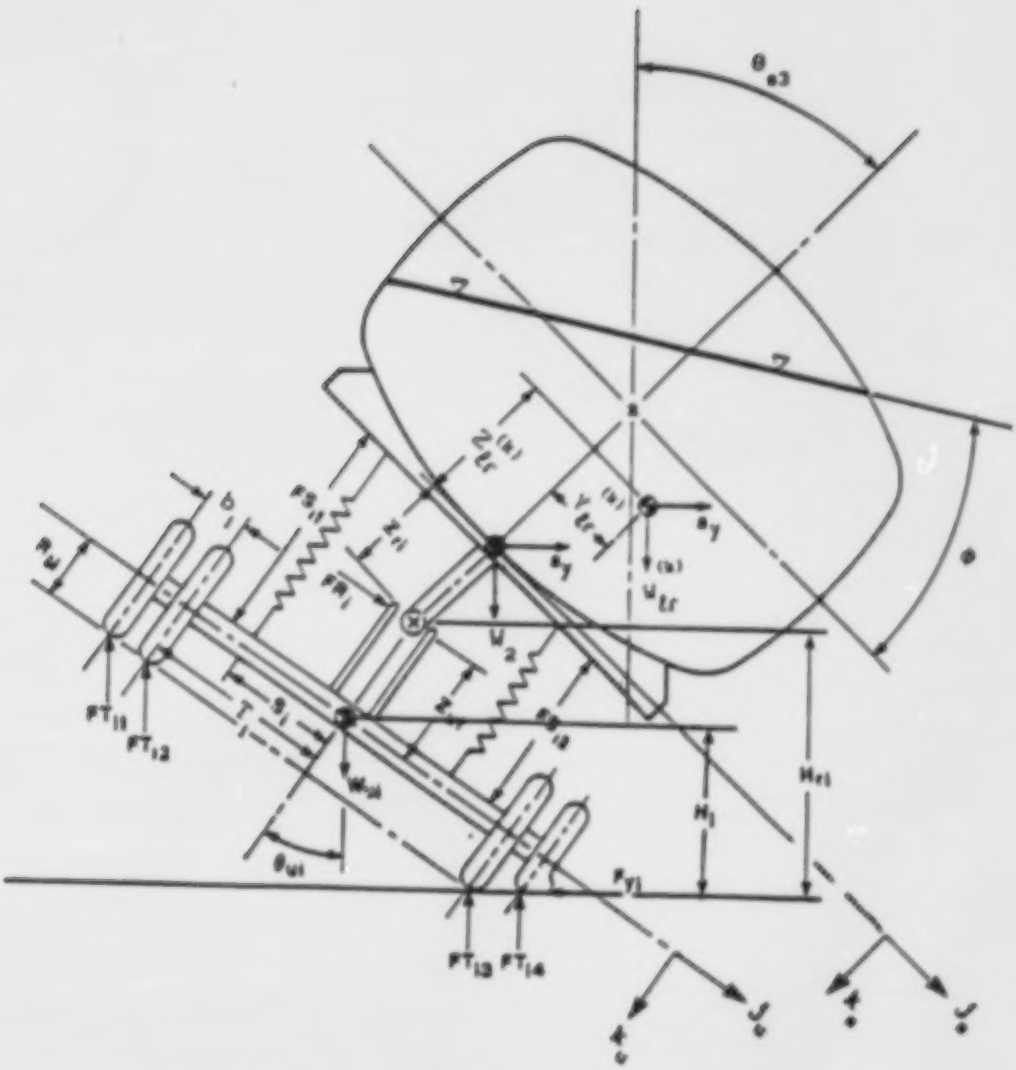


Figure 4.6: Kineto-static roll plane model of a tank vehicle.

4.2.1 EQUATIONS OF KINETO-STATIC ROLL EQUILIBRIUM

A total of 15 algebraic equations along with '2n' equations describing the load shift within *n* compartments of the tank are required to describe the kineto-static roll equilibrium of the tank vehicle. The 15 algebraic equations are obtained by balancing the roll moments acting on the sprung and unsprung weights; vertical suspension and tire forces; and lateral forces acting on the tires. A detailed derivation of the equations of roll equilibrium of an articulated tank vehicle is presented in [24].

4.3 Steady Turning Stability of Tank Vehicles

The (15+2*n*) equations describing the kineto-static roll equilibrium of a tractor-tank semitrailer vehicle are solved simultaneously to evaluate its steady turning response and rollover threshold (overturning limit). The rollover threshold levels of articulated vehicle equipped with tanks of various cross-section are compared to those of an equivalent rigid cargo vehicle to establish the influence of liquid motion within a partially filled tank vehicle. The influence of tank cross-section on steady turning overturning limits of the tank vehicles and the rollover threshold limits of compartmented tank vehicles are also investigated.

Simulation parameters of the candidate vehicle used in simulation are listed in Table 4.1. Overturning lateral acceleration limits of the tank-vehicle are evaluated for various %-fill levels where the %-fill level is defined as the percent ratio of the liquid height in compartment *k*, $h_0^{(k)}$, to the total height of the tank:

$$\%\ \text{Fill} = \begin{cases} \dfrac{h_0^{(k)}}{2R} * 100 \ ; \text{ for circular tanks} \\ \dfrac{h_0^{(k)}}{2b} * 100 \ ; \text{ for elliptical tanks} \\ \dfrac{h_0^{(k)}}{H_2} * 100 \ ; \text{ for modified-oval and square tanks} \end{cases} \tag{4.4}$$

4.3.1 LOAD SHIFT DURING STEADY TURNING

The motion of free surface of liquid within a partially filled tank can lead to significant lateral load shift during steady turning. The magnitude of lateral shift of the load depends upon gradient of the free surface, fill level, and tank cross-section. Figure 4.7 presents the lateral translation of centre of mass of liquid in circular, modified-oval, and modified-square tanks for various values of lateral acceleration and fill levels, while the tank roll is held constant (θ_{s3} = 5 degrees).

Magnitude of lateral translation of centre of mass of liquid and the

TABLE 4.1
SPECIFICATIONS OF THE TANK VEHICLE USED IN SIMULATION

TRACTOR	
Type:	Three Axle:
Sprung Weight:	46882 N (10540 lb)
Unsprung Weight (front axle):	9340 N (2100 lb)
Unsprung Weight (rear axle):	22240 N (5000 lb)
Front Axle Suspension Rating:	88960 N (20000 lb)
Rear Axle Suspension Rating:	97856 N (22000 lb)
Wheel Base:	4.37 m (172 in)

TANK and TRAILER	
Type:	Triaxle:
Sprung Weight (empty):	87448 N (19660 lb)
Tank Length:	12.19 m (480 in)
Axle Rating:	97856 N (22000 lb)
Weight Density:	0.0068 N/cm^3 (0.025 lb/in^3)
Compartment Length - I, IV:	4.06 m (160 in)
Compartment Length - II, III:	2.03 m (80 in)
Vertical spring rate of tires:	7880 N/cm (4500 lb/in)
Lateral spring rate of tires:	8755 N/cm (5000 lb/in)

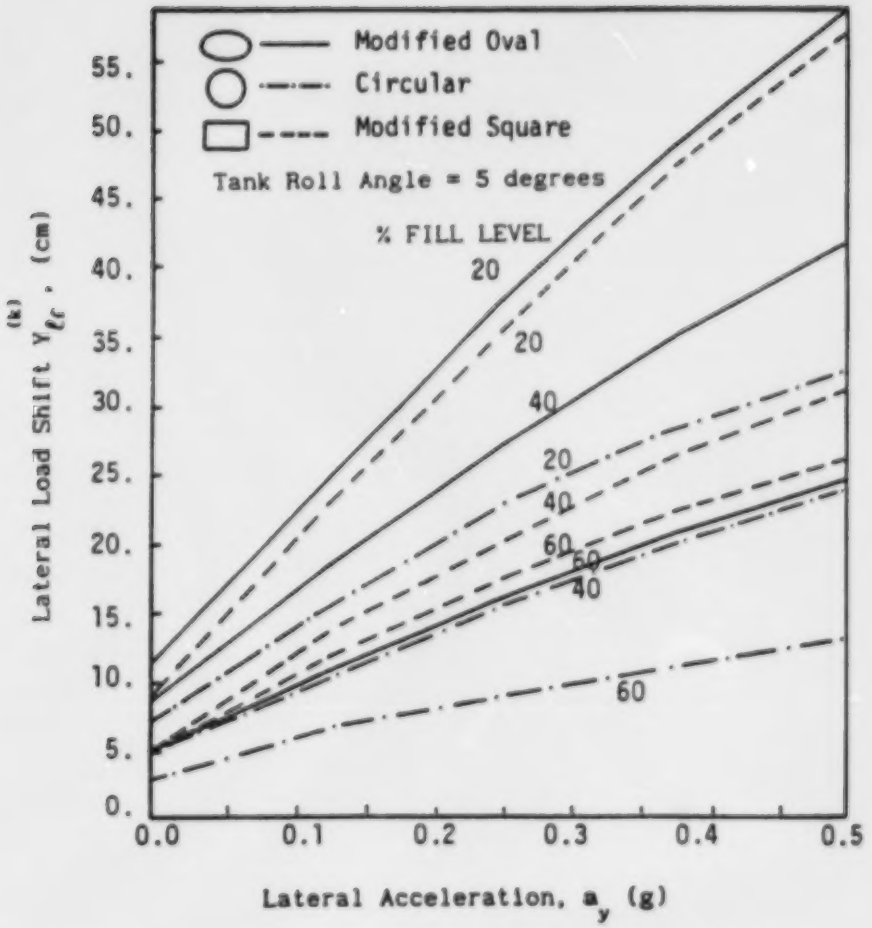


Figure 4.7: Lateral translation of C.G. of liquid due to tank roll and lateral acceleration.

lateral load shift increase significantly with the increase in vehicle acceleration. The magnitude of lateral translation of c.g. of liquid within modified-oval and modified-square tanks is significantly higher than that in a circular tank, as shown in Figure 4.7. Figure 4.8 presents a comparison of the lateral translation of the centre of mass of liquid in 40% - filled circular, modified-oval, and modified-square tanks for various acceleration levels, while the tank roll is held constant at 5 degrees. Figure 4.8 reveals, that for a lateral acceleration of 0.30 g, the lateral shift of centre of mass in a modified-oval tank is 80% greater than that in a circular tank, while the lateral shift in a modified-square tank is approximately 33% greater than that in a circular tank.

The corresponding magnitude of vertical translation of centre of mass of liquid within various tanks is only marginal, as shown in Figure 4.9. A comparison of the magnitude of vertical translation of liquid in 60% - filled circular, modified-oval, and modified-square tanks reveals that the vertical translation of centre of mass of liquid within the circular and modified-square configurations is significantly larger than that in a modified-oval tank.

4.3.2 ROLLOVER ACCELERATION LIMITS OF TANK VEHICLES

Rollover threshold acceleration of articulated tank vehicles is computed for partial fill conditions arising from two scenarios: (i) partial fill during local deliveries (variable axle loads); and (ii) partial fill due to varying weight density (constant axle loads).

Variable Axle Loads

Tank vehicles employed in local delivery routes often encounter partial fill conditions while the axle loads vary with the fill level. The rollover acceleration limits of partially filled tank vehicles are evaluated and compared to those of a vehicle carrying an equivalent rigid cargo, as shown in Figures 4.10 thru 4.13. The figures clearly illustrate that rollover threshold levels of liquid tank vehicles are significantly lower than those of vehicles carrying equivalent rigid cargo. The reduced overturning limits of the partially filled tank vehicles are attributed to the load shift occurring during steady turning. The rollover limits of tank vehicles with low fill levels are considerably lower than those of the equivalent rigid cargo due to excessive lateral load shift.

A comparison of rollover immunity levels of tank vehicles with different tank cross-sections, shown in Figure 4.14, reveals that for low fill levels, vehicles with modified-oval and modified-square tanks can rollover at lower values of lateral acceleration compared to circular cross-sectional tanks. Under 40%-fill condition, the lateral load shift caused by the motion of free surface reduces the rollover threshold acceleration of a circular tank by 0.11 g and that of an elliptic tank by 0.12 g. The rollover threshold limits, of modified-oval and modified-square tank configurations, are reduced respectively by 0.17 g and 0.20 g, compared to that of an equivalent rigid cargo vehicle. The rollover limits of tank vehicles approach that of an equivalent rigid cargo vehicle for fill levels greater than 90%.

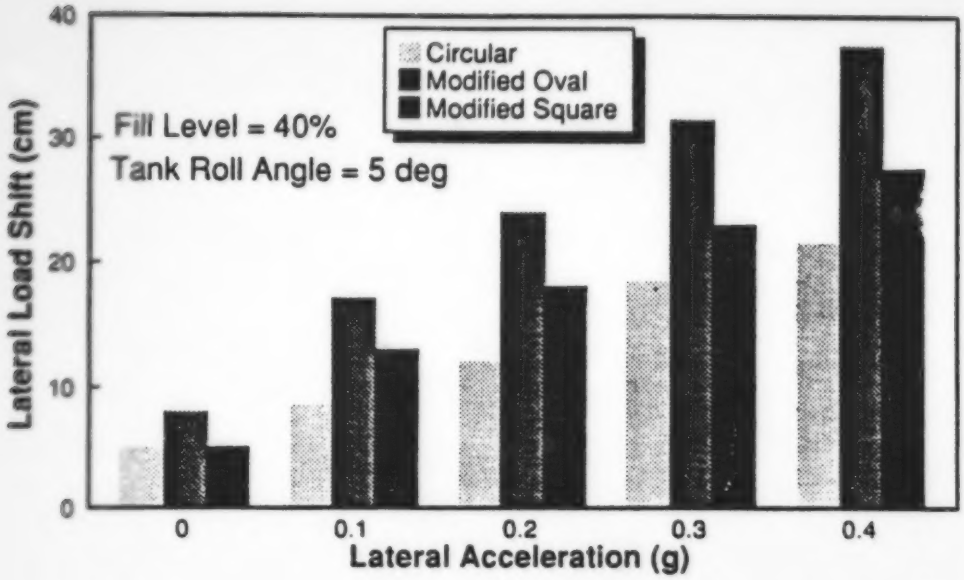


Figure 4.8: Comparison of lateral translation of C.G of liquid within different cross-section tanks.

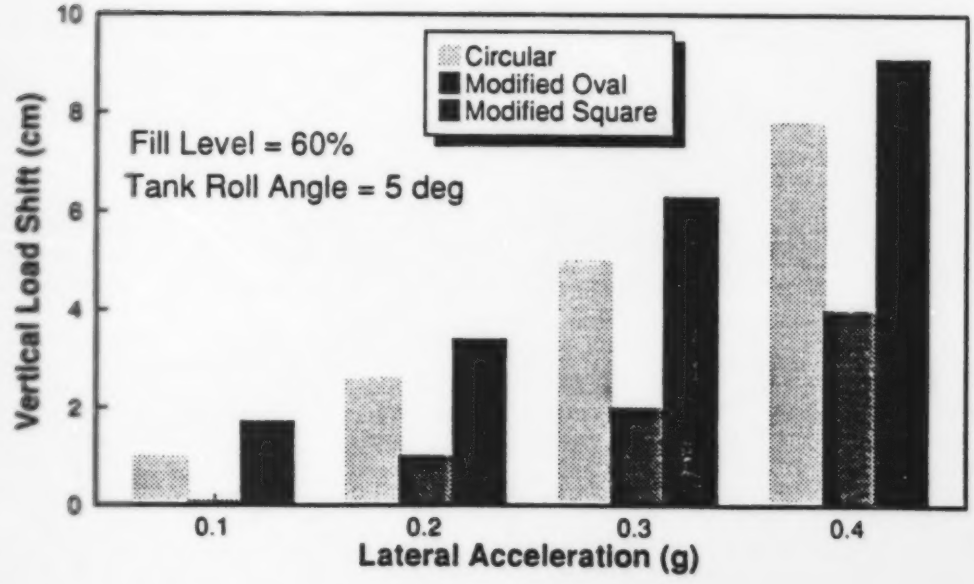


Figure 4.9: Comparison of vertical translation of C.G. of liquid within different cross-section tanks.

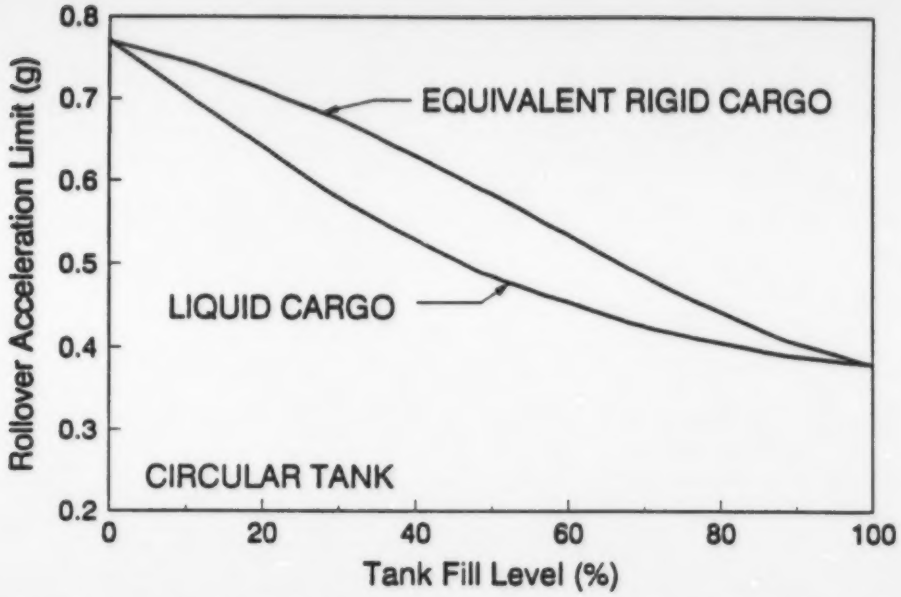


Figure 4.10: Rollover threshold acceleration of equivalent rigid cargo and circular tank vehicles (Variable axle loads).

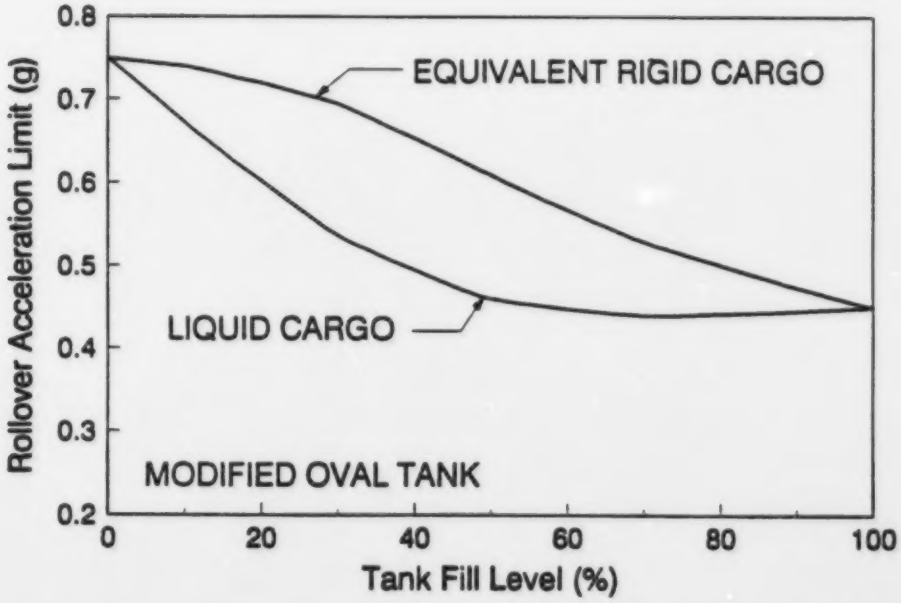


Figure 4.11: Rollover threshold acceleration of equivalent rigid cargo and modified-oval tank vehicles (Variable axle loads).

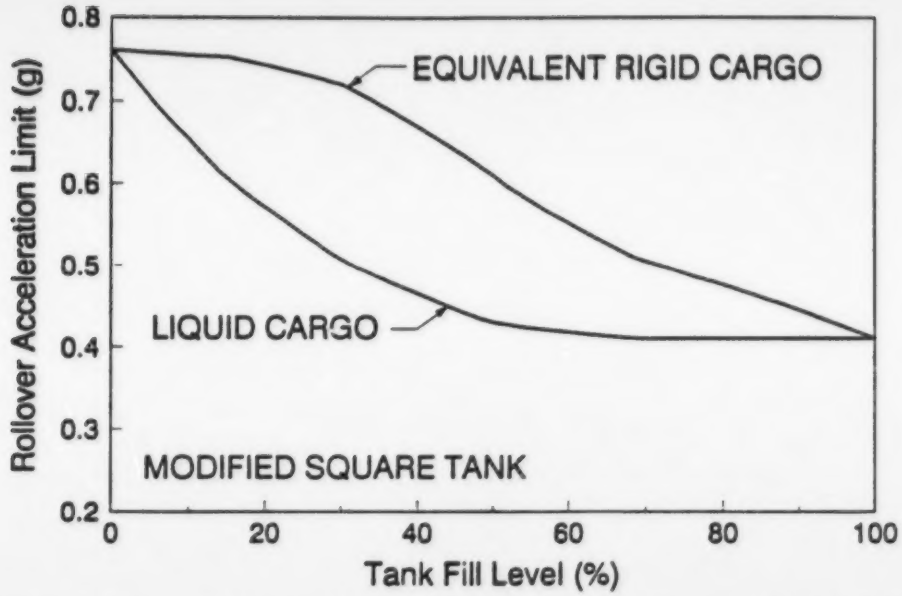


Figure 4.12: Rollover threshold acceleration of equivalent rigid cargo and modified-square tank vehicles (Variable axle loads).

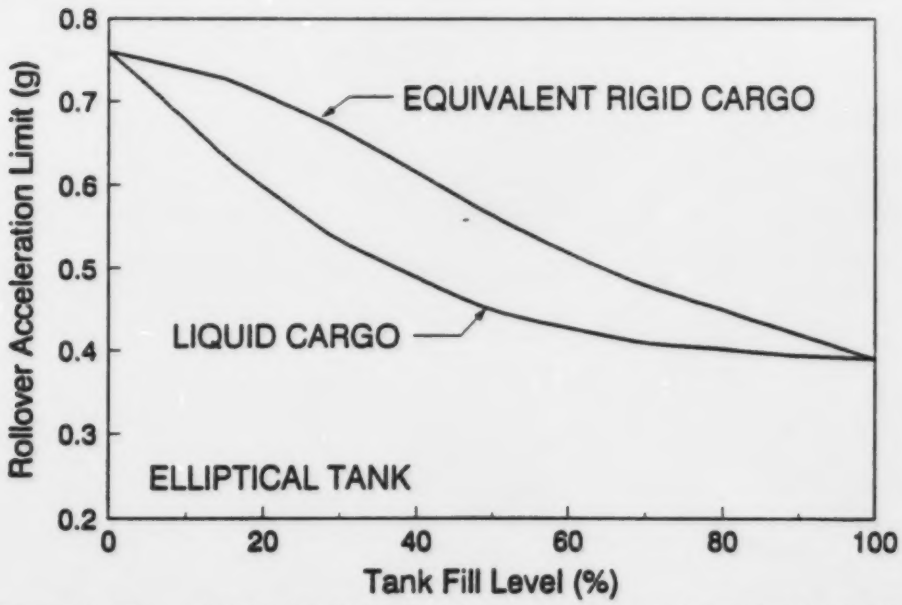


Figure 4.13: Rollover threshold acceleration of equivalent rigid cargo and elliptic tank vehicles (Variable axle loads).

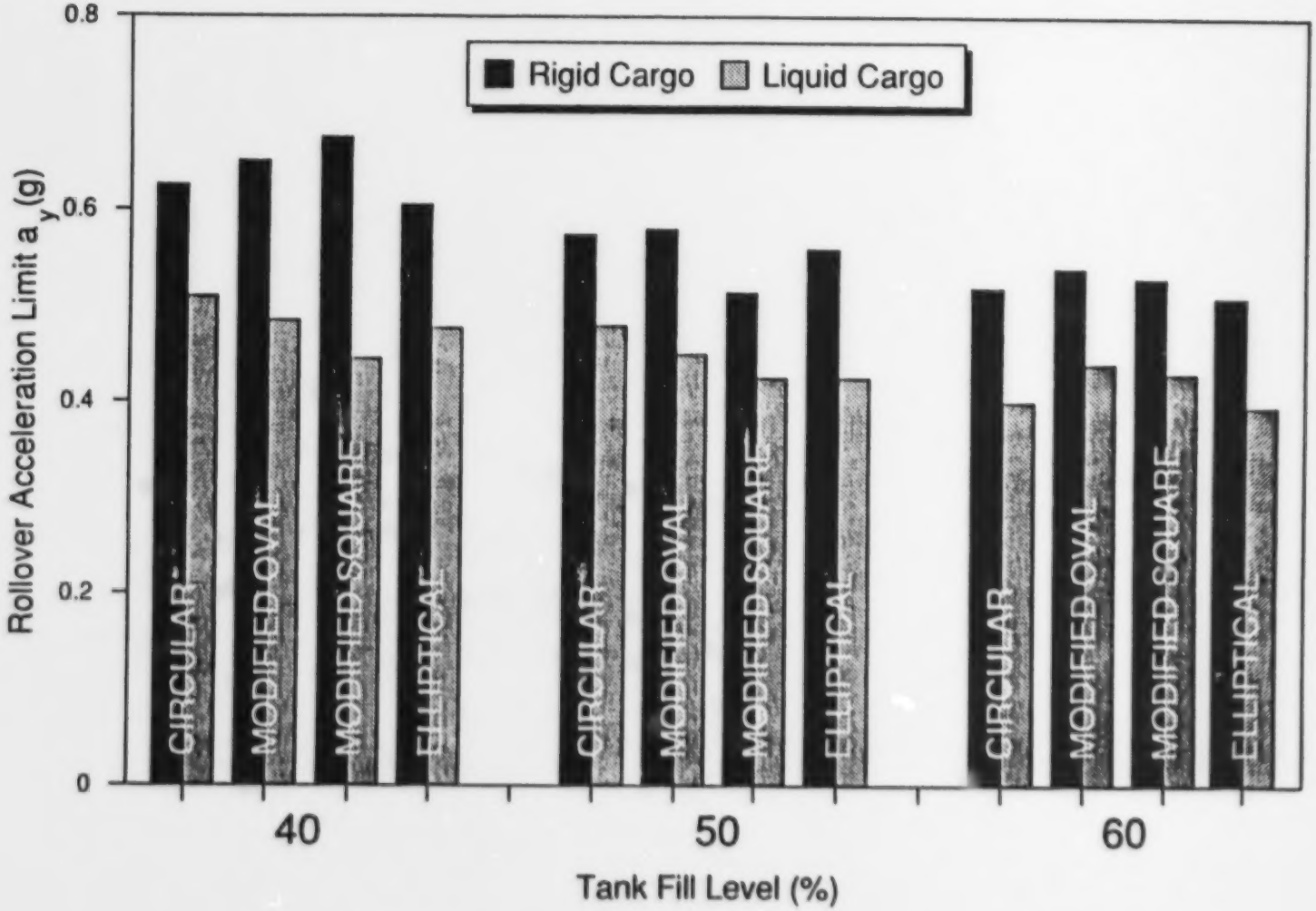


Figure 4.14: Comparison of rollover acceleration limits of tank vehicles with various tank cross-sections (Variable axle loads).

Constant Axle Loads

Tank vehicles used in a general purpose chemical fleet often carry partial loads due to variations in weight density of chemicals. The axle loads, however, are maintained near the maximum permissible values. The rollover acceleration limits of partially filled tank vehicles are compared to those of the equivalent rigid cargo vehicles, while the load carried by each composite axle is maintained constant by varying the weight density of the liquid carried, as illustrated in Figures 4.15 to 4.18. The 100%-fill condition and corresponding composite axle loads are based upon fuel oil of weight density 0.0068 N/cm^3. The rollover immunity of the vehicle for partial fill conditions is evaluated by varying the weight density, while the composite axle loads are kept constant.

The rollover acceleration limit of an equivalent rigid cargo vehicle increases rapidly due to reduced centre of mass height of the sprung weight. In the case of circular tank vehicles, expected increase in the rollover threshold limits, due to reduced centre of mass height, is compensated by the load shift occurring during partial filling of the tank. Hence, the rollover threshold value remains almost constant irrespective of the fill level, as shown in Figure 4.15. The rollover threshold limits of modified-oval, modified-square, and elliptical tanks, however, decrease for denser chemicals (low fill levels), as shown respectively in Figures 4.16 to 4.18. The reduction in rollover threshold limits is attributed to larger lateral load shift encountered in modified-oval, modified-square, and elliptical tanks compared to cylindrical tanks.

The rollover immunity levels of tank vehicles with circular, elliptical, modified-oval, and modified-square tank configurations carrying liquids of different weight densities at constant axle loads are summarized in Figure 4.19. The total payload is held fixed at approximately 268 kN (60320 lbs). The modified-oval and modified-square tanks exhibit improved threshold limits while carrying lighter liquids, whereas the circular tanks show better stability for denser liquids.

4.3.3 ROLLOVER THRESHOLD LIMITS OF COMPARTMENTED TANK VEHICLES

In view of the reduced rollover threshold value of partially filled tank vehicles, compartmented tanks are often used to minimize the occurrence of partial fill conditions. Specifically, vehicles delivering fuel oils within a city employ compartmented tanks so that one or more of the compartments may be emptied completely while the remaining compartments carry full loads. Often semitrailer vehicles carry tanks with 4 or 5 compartments. The rollover limits of such vehicles depend upon the load distribution among the various compartments.

The rollover threshold of a tank vehicle equipped with a four compartmented tank of modified-oval cross-section, as shown in Figure 4.20, is investigated. The rollover acceleration limits of the four compartmented tank vehicle with one of the compartments carrying partial load and the other compartments fully loaded is presented in Figure 4.21. The tank vehicle exhibits highest rollover limit when compartment II is partially filled for fill levels below 50%. For fill levels greater than 50%, partial fill in

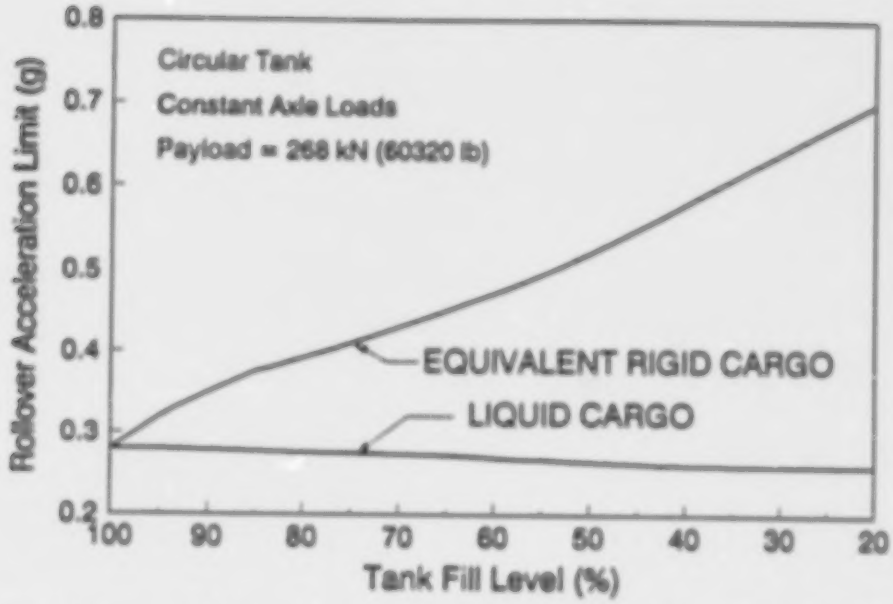


Figure 4.15: Rollover threshold acceleration of equivalent rigid cargo and circular tank vehicles (Constant axle loads).

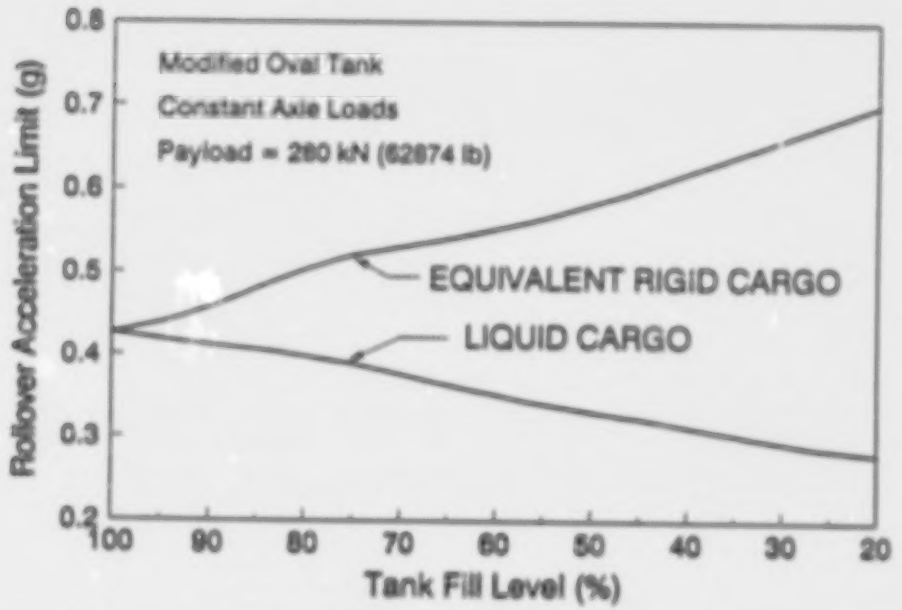


Figure 4.16: Rollover threshold acceleration of equivalent rigid cargo and modified-oval tank vehicles (Constant axle loads).

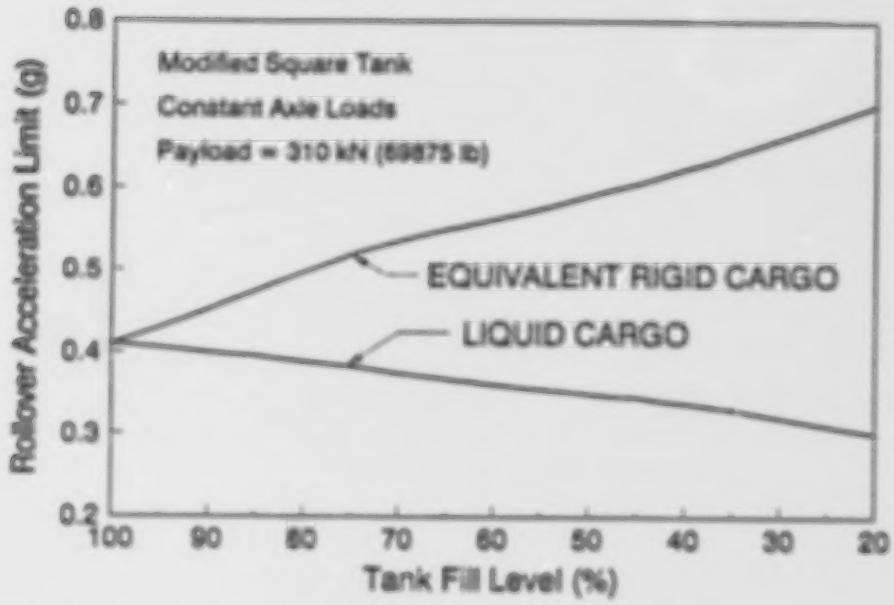


Figure 4.17: Rollover threshold acceleration of equivalent rigid cargo and modified-square tank vehicles (Constant axle loads).

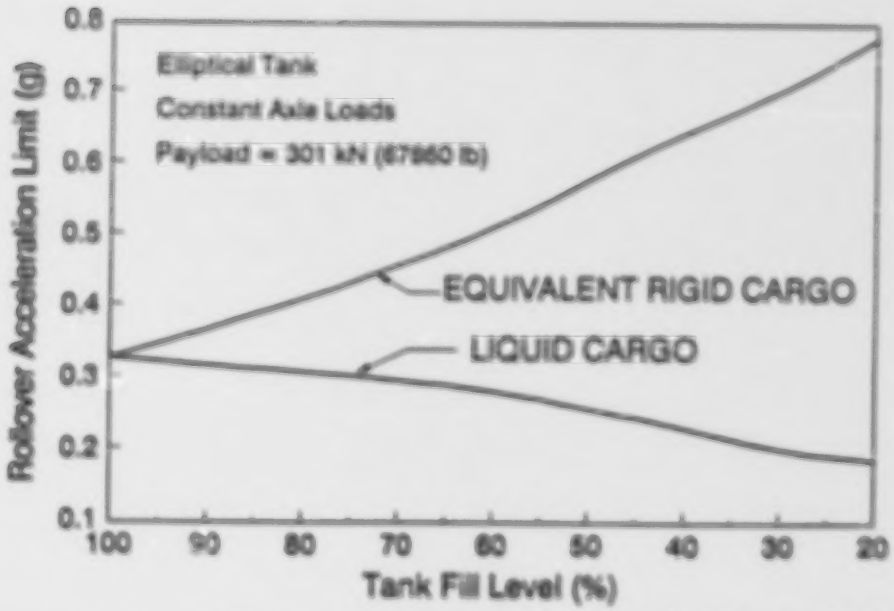


Figure 4.18: Rollover threshold acceleration of equivalent rigid cargo and elliptic tank vehicles (Constant axle loads).

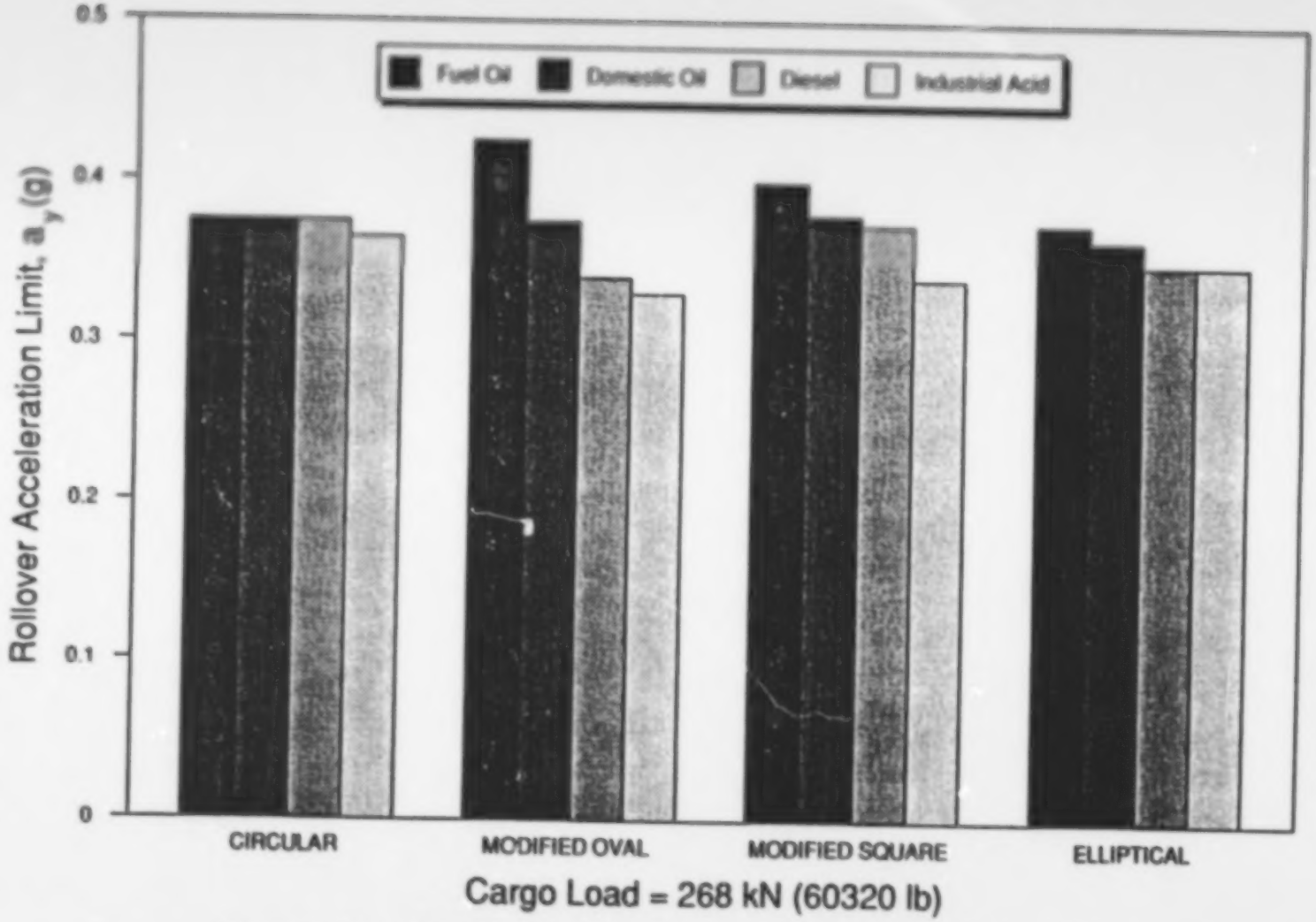


Figure 4.19: Comparison of rollover acceleration limits of tank vehicles with various tank cross-sections (Constant axle loads).

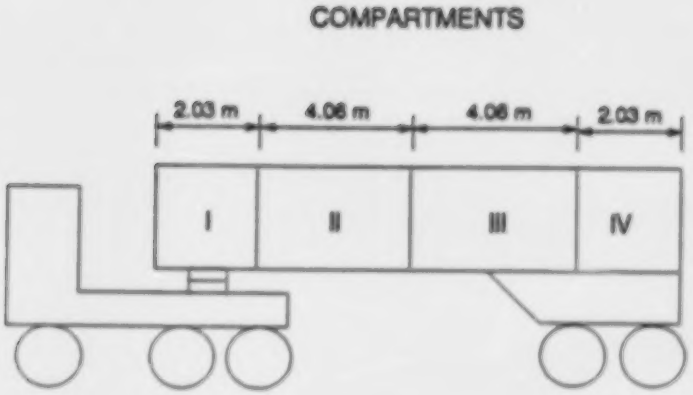


Figure 4.20: Schematic of a compartmented tank vehicle.

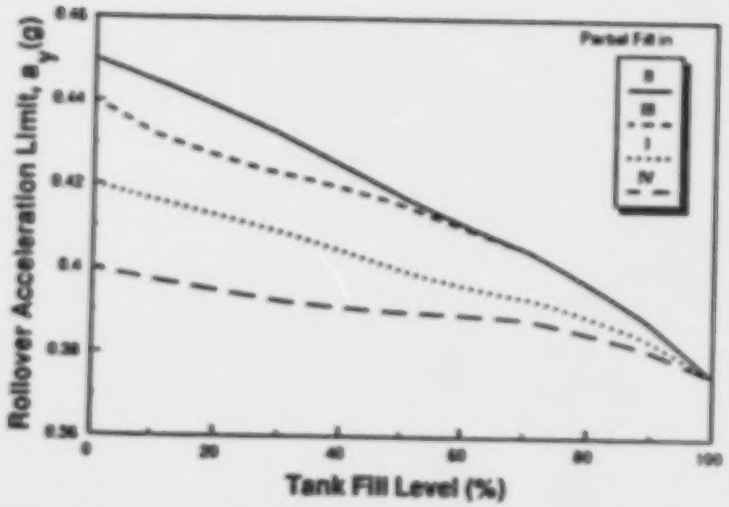


Figure 4.21: Rollover acceleration limits of a compartmented tank vehicle.

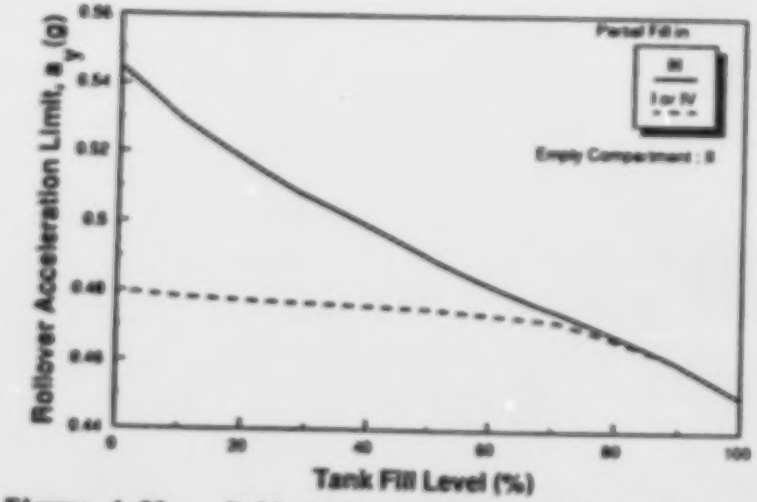


Figure 4.22: Rollover acceleration limits of a compartmented tank vehicle with one compartment empty.

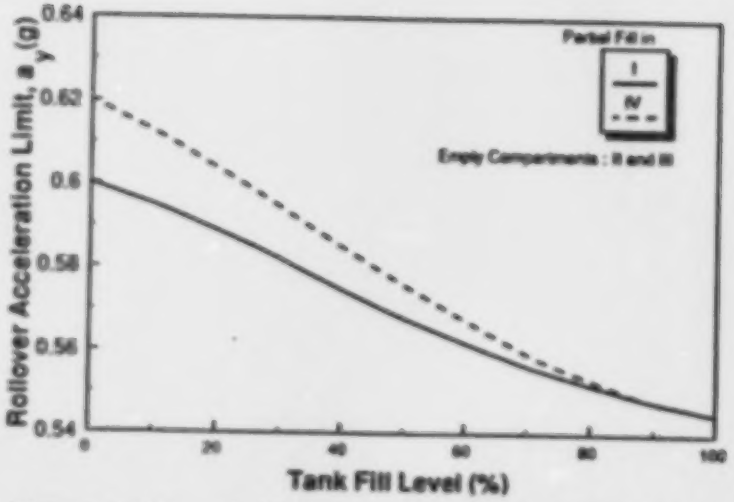


Figure 4.23: Rollover acceleration limits of a compartmented tank vehicle with two compartments empty.

compartments II or III yields almost identical overturning limit. Partial filling of compartment IV yields minimum value of rollover acceleration limit due to reduction in load carried by the trailer composite axle. Thus, under partial fill conditions, compartment II must be emptied first in order to achieve highest value of rollover limit of the vehicle.

The rollover threshold values of a tank vehicle with an empty compartment (II) and one partially filled compartment are presented in Figure 4.22. A partial load in compartment III reveals a higher value of rollover acceleration limit when compared to that of a partially filled compartment I and IV. In the event that two of the compartments are required to be empty and another compartment is to carry partial load, it is appropriate to keep the mid-compartments of the tank (II and III) empty, while the fill level in compartments I and IV may be varied. The rollover acceleration limits for such a tank vehicle is presented in Figure 4.23, for various fill levels in either compartment I or IV, while the mid-compartments are empty. It can be observed, that for fill levels less than 70%, the partial load in compartment I yields higher values of the overturning acceleration limits of the vehicle. Thus a theoretical "order of unloading" the various compartments can be proposed to achieve the best values of vehicle rollover acceleration limits. From Figures 4.21 to 4.23, it can be concluded that the "order of unloading" a four-compartment tank vehicle, shown in Figure 4.20, is II, III, I and IV. In general, the order of unloading the various compartments, however, is dependent on a number of vehicle design factors, such as compartment location, capacity of various compartments, and the location of trailer's composite axle.

5. DIRECTIONAL DYNAMICS OF TANK VEHICLES

Potential safety hazards posed by partially filled tank vehicles are directly related to their directional dynamics and stability limits. The roll plane model, presented in Section 4, provides only steady-state stability limits of the vehicles during a steady turning manoeuvre. The stability limits of partially filled tank vehicles may be further deteriorated during high speed directional manoeuvres. Partially filled tank vehicles exhibit unstable behaviour at lateral acceleration levels considerably lower than the rollover threshold when executing high speed directional manoeuvres. It is thus vital to examine the stability of tank vehicles for various highway manoeuvres such as lane change and evasive manoeuvres. A directional dynamic model of the tank vehicle has been developed to compute the directional response to transient steering manoeuvres. The model is capable of evaluating the directional response of tank vehicles equipped with tanks of circular or modified-oval cross-sections for both open-loop steer and closed-loop path follower manoeuvres.

5.1 Quasi-Dynamic Model of a Partially Filled Tank

A directional dynamic model of a tank vehicle is formulated by integrating a steady-state roll plane model of fluid slosh to a three-dimensional vehicle dynamics model assuming constant forward speed. The steering frequency is assumed to be well below the fundamental slosh frequency and the dynamic load transfer is computed assuming inviscid fluid flow conditions. The dynamic load shift and instantaneous mass moment of inertia are strongly related to tank cross-section, fill level, and free surface gradient. An iterative procedure is developed to compute the dynamic load transfer and instantaneous mass moment of inertia of the fluid within circular and modified-oval tanks.

Gradient of the free surface is determined from instantaneous tank roll angle and lateral acceleration, using the following expression:

$$\tan \phi_f = \left(\frac{\theta_{sf} + a_{\ell f}}{1 - a_{\ell f} \theta_{sf}} \right) \tag{5.1}$$

where ϕ_f is gradient of the free surface of liquid within a tank, θ_{sf} and $a_{\ell f}$ are roll angle and lateral acceleration of semitrailer's sprung mass, expressed in radians and g units respectively, and

$$f = \begin{cases} 2 & ; \text{ for a tractor-semitrailer vehicle} \\ 2,3 & ; \text{ for a B-train vehicle} \end{cases} \tag{5.2}$$

The dynamic load transfer is computed from the corresponding vertical and lateral translation of centre of mass of liquid bulk, described in Section 4 (Eqns. 4.2 and 4.3).

The moments of inertia of displaced liquid cargo are derived about a coordinate system attached to its centre of mass. The displaced liquid cargo is split into a number of thin sections in the roll plane, as illustrated in Figure 5.1. The mass moments of inertia of the displaced fluid bulk are then obtained by summing the mass moments of inertia of individual sections about the overall centre of mass of the fluid. For symmetrical tanks, the moments of inertia remain identical about the axis of symmetry. The moments of inertia of displaced liquid within a circular cross-section tank are then computed using the gradient of the free surface of the liquid:

$$
\begin{aligned}
I_{x\ell f} &= I_{x\ell o} \\
I_{y\ell f} &= I_{y\ell o}\cos^2(\phi_f) + I_{z\ell o}\sin^2(\phi_f) \\
I_{z\ell f} &= I_{z\ell o}\cos^2(\phi_f) + I_{y\ell o}\sin^2(\phi_f)
\end{aligned}
\qquad (5.3)
$$

where $I_{x\ell o}$, $I_{y\ell o}$, $I_{z\ell o}$ are mass moments of inertia of liquid mass under static conditions. Computation of mass moments of inertia of liquid bulk within a partially filled modified-oval tank is quite involved due to the complex geometry. The mass moments of inertia of liquid within a modified-oval tank, obtained about the rotated sprung mass axes using a transformation matrix, are expressed as:

$$
\begin{aligned}
I_{x\ell f} &= I'_{x\ell} \\
I_{y\ell f} &= I'_{y\ell}\cos^2(\theta_{sf}) + I'_{z\ell}\sin^2(\theta_{sf}) \\
I_{z\ell f} &= I'_{z\ell}\cos^2(\theta_{sf}) + I'_{y\ell}\sin^2(\theta_{sf})
\end{aligned}
\qquad (5.4)
$$

where $I'_{x\ell}$, $I'_{y\ell}$, $I'_{z\ell}$ are the moments of inertia of the displaced shape of liquid in a modified-oval tank.

5.2 Development of the Vehicle Dynamics Model

A directional dynamic model of the selected vehicle configurations is developed using the methodology described in [14]. Each tank trailer/semitrailer unit is represented by two sprung weights: (*i*) tare sprung weight due to empty tank and semitrailer structure; and (*ii*) liquid sprung weight which is considered a floating weight with respect to the centre of mass of the tare weight. Each sprung weight of the tank vehicle combination is modeled as a rigid body with five-degrees-of-freedom: lateral, vertical, yaw, roll, and pitch. The unsprung weights are free to roll and bounce with respect to the sprung weights to which they are attached. Figure 5.2 presents the roll and pitch planes of a B-train tank vehicle model, and the various coordinate systems attached to the sprung and unsprung masses. The constraint forces at the couplings are evaluated from kinematic expressions relating the acceleration of the tractor and tank trailer tare sprung weights. The constraint moments are evaluated from the relative angular displacement between the tractor and semitrailer sprung weights.

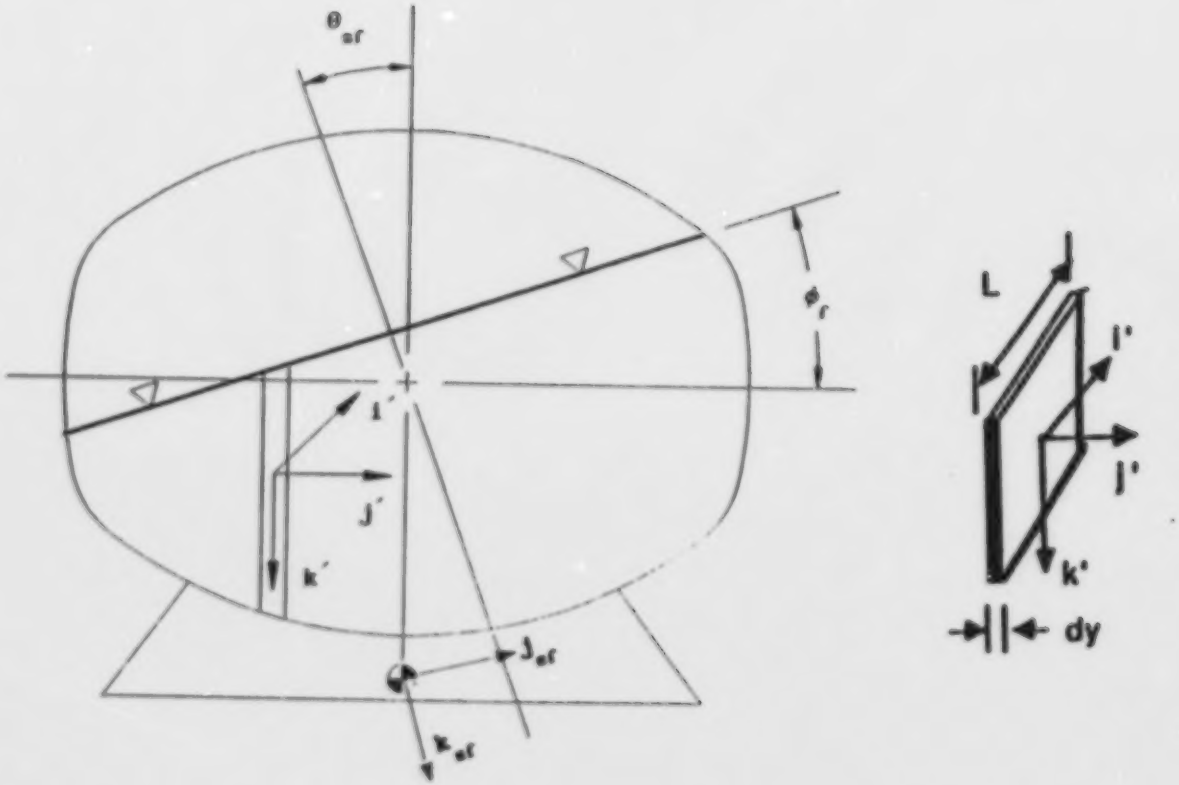


Figure 5.1: Computation of the mass moment of inertias.

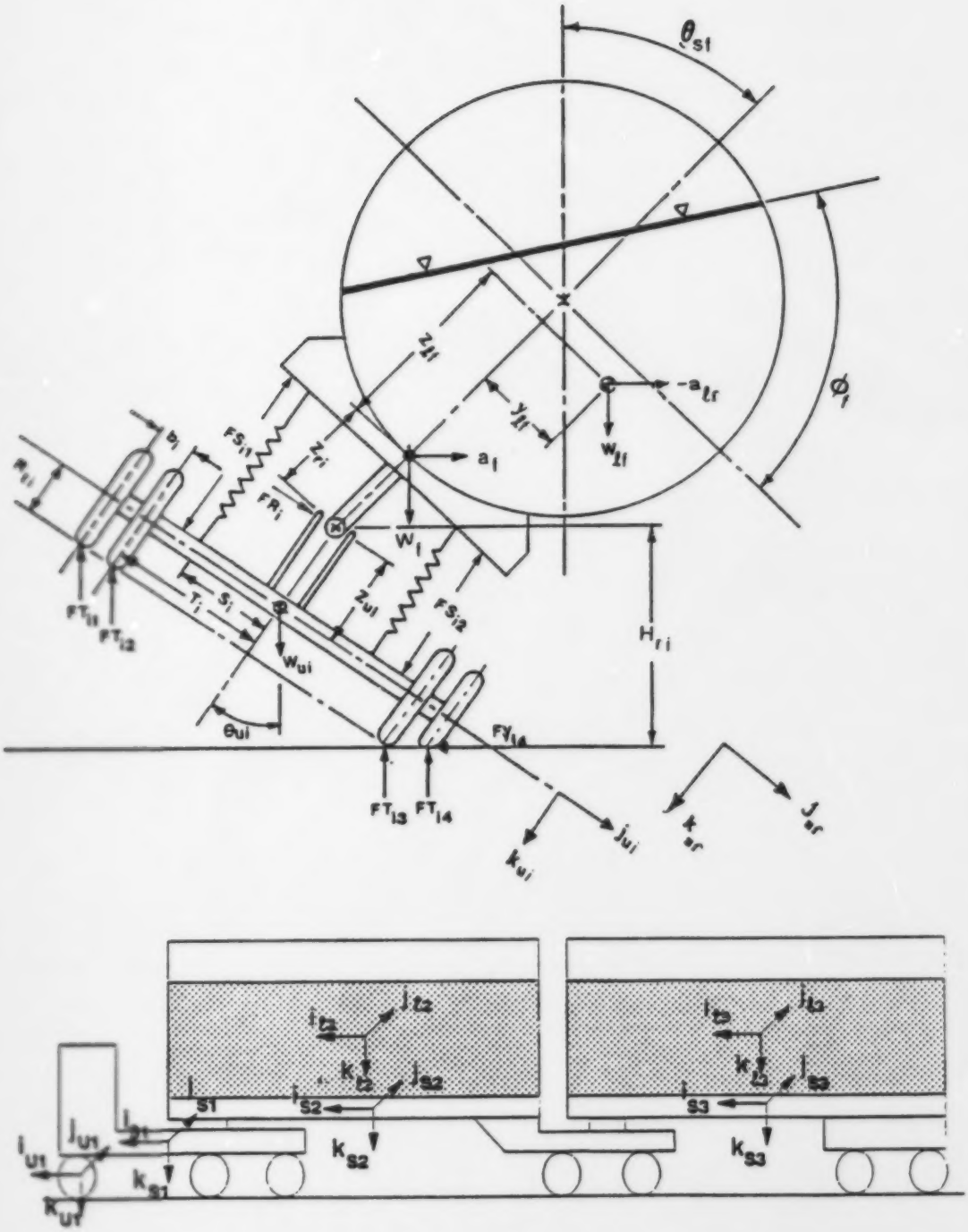


Figure 5.2: Roll and pitch plane models of a tank vehicle combination

5.3 Model Assumptions

The equations of motion for selected tank vehicle configurations are developed based on a number of simplifying assumptions [14,26]. The vehicle is assumed to move at constant speed on a horizontal surface possessing even frictional properties. The pitch rotations (α_{sf}) are assumed to be small, so that $\sin \alpha_{sf} = \alpha_{sf}$ and $\cos \alpha_{sf} = 1$. The relative roll between the sprung and unsprung weights are also considered to be small, and the sprung units are assumed to roll about the roll centre located at a fixed distance below the sprung weight's centre of mass.

Suspension forces are assumed to act along the vertical axis of the corresponding unsprung mass with only compression and tensile forces being transmitted to the sprung mass. The roll centre is free to move along the vertical axis of the unsprung mass such that the lateral forces acting on the roll centre remain parallel to the horizontal axis of the unsprung mass. The nonlinear spring characteristics are linearized about the operating point using a look-up table. The principal axes of inertia of the sprung masses and the unsprung masses are assumed to coincide with their respective body-fixed coordinate systems. The cornering forces and aligning moments due to tires are determined as nonlinear functions of side slip angles and normal loads. The vertical load on each tire is computed from the instantaneous tire deflection and the vertical tire stiffness.

5.4 Equations of Motion

Equations of motion are derived to describe the directional dynamics of various vehicle configurations with liquid cargo. The directional dynamic model of the tank vehicle is formulated by integrating the steady-state fluid motion to the three-dimensional vehicle dynamics model. The equations of motion describing the directional dynamics of articulated tank vehicles are derived as follows:

Equations of Lateral Motion

$$m_f a_f \vec{J}_{sf} + m_{\ell f} a_{\ell f} \vec{J}_{sf} = \text{(Lateral components of constraint and suspension forces)} + (m_f + m_{\ell f}) g \, \theta_{sf} \qquad (5.5)$$

Equations of Vertical Motion

$$m_f a_f \vec{k}_{sf} + m_{\ell f} a_{\ell f} \vec{k}_{sf} = \text{(Vertical components of constraint and suspension forces} + (m_f + m_{\ell f}) g \qquad (5.6)$$

Equations of Roll Motion

$$(I_{xf} + I_{x\ell f})\,\dot{p}_f - (I_{yf} + I_{y\ell f} - I_{zf} - I_{z\ell f})\,q_f r_f =$$

(Roll moments due to constraint and suspension forces)

$$+m_{\ell f} a_{\ell f}\,\vec{J}_{sf} Z_{\ell f} + m_{\ell f} a_{\ell f}\vec{k}_{sf} Y_{\ell f} + m_{\ell f} g\,(\theta_{sf} Z_{\ell f} + Y_{\ell f}) \qquad (5.7)$$

Equations of Pitch Motion

$$(I_{yf} + I_{y\ell f})\,\dot{q}_f - (I_{zf} + I_{z\ell f} - I_{xf} - I_{x\ell f})\,p_f r_f =$$

(Pitch moments due to constraints and suspension forces)

$$- m_{\ell f}\, a_{\ell f}\vec{k}_{sf}\, X_{\ell f} - m_{\ell f}\, a_{\ell f}\vec{I}_{sf}\, Z_{\ell f} - m_{\ell f} g\,(X_{\ell f} + \alpha_{sf}\, Z_{\ell f}) \qquad (5.8)$$

Equations of Yaw Motion

$$(I_{zf} + \sum_{i=N_1}^{N_2} I_{zui} + I_{z\ell f})\,\dot{r}_f - (I_{xf} + I_{x\ell f} - I_{yf} - I_{y\ell f})\,p_f q_f =$$

(Yaw moments due to constraint and suspension forces)

$$+ m_{\ell f} a_{\ell f}\vec{I}_{sf}\, Y_{\ell f} + m_{\ell f} a_{\ell f}\vec{J}_{sf} X_{\ell f} \qquad (5.9)$$

Equations of Unsprung Mass Roll Motion

$$I_{xui}\dot{p}_{ui} = \text{(Roll moments due to tire and suspension forces)} \qquad (5.10)$$

Equations of Unsprung Mass Vertical Motion

$$m_{ui} a_{ui}\vec{k}_{ui} = \text{(Vertical components of tire and suspension forces)} + m_{ui} g \qquad (5.11)$$

where a_f and a_{ui} are the acceleration vectors of the sprung mass f and unsprung mass i respectively, and $a_{\ell f}$ is the acceleration vector of liquid mass. (p_f, q_f, r_f) are the rotational velocities of sprung mass f and p_{ui} is the roll velocity of axle i.

Liquid Mass Acceleration

The entire fluid bulk is assumed to move as a rigid body, due to tank roll and lateral acceleration imposed by the vehicle. The roll, pitch and yaw velocities of the liquid bulk are thus assumed to be equal to those of the

trailer sprung weight. Acceleration of the liquid bulk $a_{\ell f}$, is computed from acceleration of the trailer sprung weight a_f, and the instantaneous location of centre of gravity (c.g.) of the liquid bulk with respect to the trailer c.g..

$$a_{\ell f} = a_f + a_{\ell f/f} \; ; \; f = 2,..,\eta_\ell \tag{5.12}$$

where η_ℓ is the number of liquid masses and $a_{\ell f/f}$ is the acceleration of liquid c.g. with respect to c.g. of the tank trailer f, given by:

$$\begin{aligned} a_{\ell f/f} = {} & (\dot{q}_f Z_{\ell f} - \dot{r}_f Y_{\ell f} - q_f^2 X_{\ell f} + p_f q_f Y_{\ell f} + r_f p_f Z_{\ell f} - r_f^2 X_{\ell f})\vec{I}_{sf} \\ & + (-\dot{p}_f Z_{\ell f} + \dot{r}_f X_{\ell f} - p_f^2 Y_{\ell f} + p_f q_f X_{\ell f} + r_f q_f Z_{\ell f} - r_f^2 Y_{\ell f})\vec{J}_{sf} \\ & + (\dot{p}_f Y_{\ell f} - \dot{q}_f X_{\ell f} - p_f^2 Z_{\ell f} + p_f r_f X_{\ell f} - r_f q_f Y_{\ell f} + q_f^2 Z_{\ell f})\vec{k}_{sf} \end{aligned} \tag{5.13}$$

where (u_f, v_f, w_f) are linear velocities of the sprung mass f along the sprung mass coordinate, and $(X_{\ell f}, Y_{\ell f}, Z_{\ell f})$ are the coordinates of the instantaneous centre of mass of liquid with respect to the tank trailer c.g.

Constraint Equations

Differential equations (5.5) through (5.9), describing the motion of sprung masses of tank vehicle combinations, include constraint forces and moments arising from fifth wheel couplings. The constraint forces are evaluated from kinematic expressions that relate the accelerations at the constraint point due to the sprung masses attached to it. The constraint moments are calculated as a function of the relative angular displacement of the sprung masses. A detailed derivation of constraint forces and moments, and equations of motion of various tank vehicle combinations is presented in reference [26].

The set of second order differential equations describing the motion of the tank vehicle combination can be expressed as:

$$\ddot{\mathbf{x}} = \mathbf{M}^{-1} \mathbf{f}_c + \mathbf{M}^{-1} \mathbf{N} [\mathbf{C}\mathbf{M}^{-1}\mathbf{N}]^{-1} (\mathbf{d} - \mathbf{C}\mathbf{M}^{-1}\mathbf{f}_c) \tag{5.14}$$

where **M** is the inertia matrix, $\ddot{\mathbf{x}}$ is the acceleration vector, $\mathbf{f}_c$ is the vector comprising gravitational, suspension, roll centre, and liquid slosh forces and moments, **N** is a transformation matrix containing vehicle dimensions and velocities, and

$$\mathbf{C}\ddot{\mathbf{x}} = \mathbf{d} \tag{5.15}$$

where **C** is a matrix of vehicle dimensions, and **d** is a vector, containing

displacements x, velocities $\dot{x}$, and vehicle dimensions.

Directional dynamics and stability limits of tank vehicles may be evaluated for both closed-loop and open-loop steer manoeuvres using equation (5.14). In an open-loop steer manoeuvre, the time history of steer input to the front wheels is required, while trajectory of the path to be followed is specified during a closed-loop steer manoeuvre. Equation (5.14) is solved via numerical integration to yield the directional response characteristics of the vehicle combination for a given vehicle manoeuvre.

5.5 Directional Response of a Tractor-Semitrailer - Cleanbore Cylindrical Tank

The three-dimensional vehicle dynamics model incorporating steady-state roll plane fluid slosh model of the partially filled tank is solved for various directional manoeuvres to determine the transient directional response and thus the dynamic stability of candidate tank vehicle combinations. The influence of fill level, vehicle speed, tank shape, compartments, and severity of the directional manoeuvre on the directional stability of tank vehicle combinations are extensively investigated and discussed. The transient directional response characteristics of the tank vehicles are compared to those of an equivalent rigid cargo vehicle in order to demonstrate the adverse influence of liquid motion within the partially filled tanks.

Cleanbore cylindrical tanks used in general purpose chemical fleet are often partially filled due to variations in the weight density of various chemicals. Computer simulations are performed to determine the directional response characteristics of tractor-semitrailer vehicles employed in general purpose chemical fleets. Directional response characteristics are evaluated for five-, six- and seven-axle tractor-semitrailer vehicles subjected to constant steer, lane change and evasive manoeuvres. The load carried by each axle, however, is maintained around the maximum permissible values.

5.5.1 CONSTANT STEER MANOEUVRES

Computer simulations are performed for a constant or a modified step steer manoeuvre, where the steer angle initially increases as a ramp function until it reaches a specified value and thereafter the steer axle is held constant during the entire simulation. Directional response parameters, such as roll angle, roll rate, lateral acceleration and vehicle path are evaluated for both liquid as well as rigid cargo.

Computer simulations are performed to investigate the directional response of 40%- and 70%- filled tractor-semitrailer tank vehicles carrying industrial acid (weight density = 0.0186 N/cm^3 or 0.0673 lb/in^3) and diesel oil (weight density = 0.0092 N/cm^3 or 0.034 lb/in^3), respectively.

Five-Axle Tractor-Semitrailer (Two-axle semitrailer)

Axle loads are held constant around the maximum permissible values (tractor's front axle: 55 kN; tractor's rear axle group: 170 kN; and semitrailer axle group: 170 kN). Figure 5.3 presents the roll angle and lateral acceleration response of 40%- and 70%- filled tank and equivalent rigid cargo vehicles for steady steer inputs of 1 and 3 degrees at a speed of

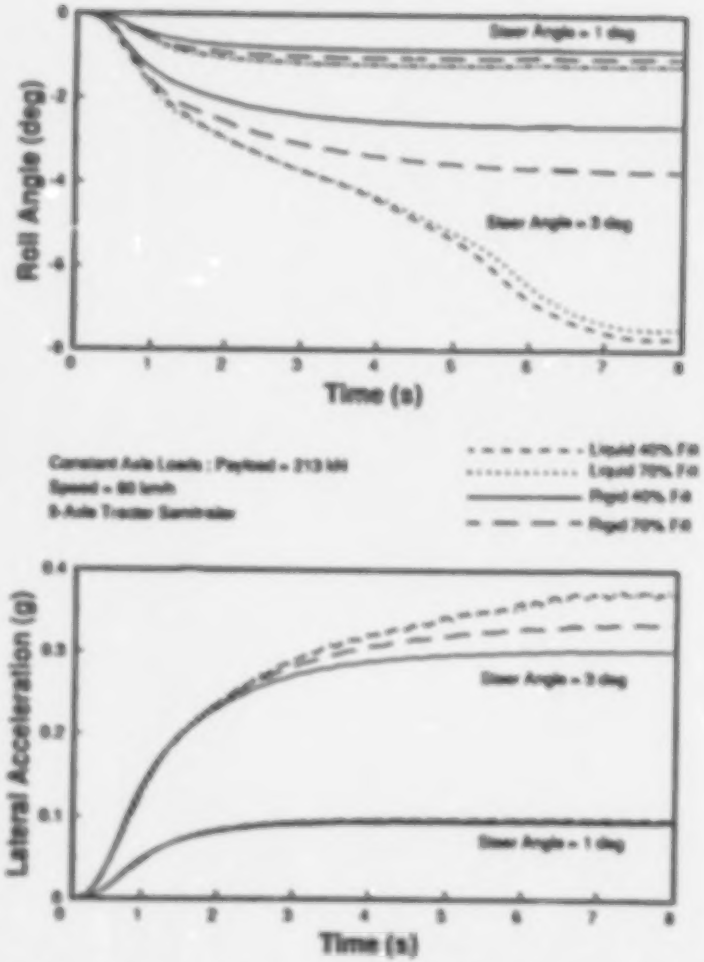


Figure 5.3: Transient directional response of semitrailer with liquid and equivalent rigid cargo.

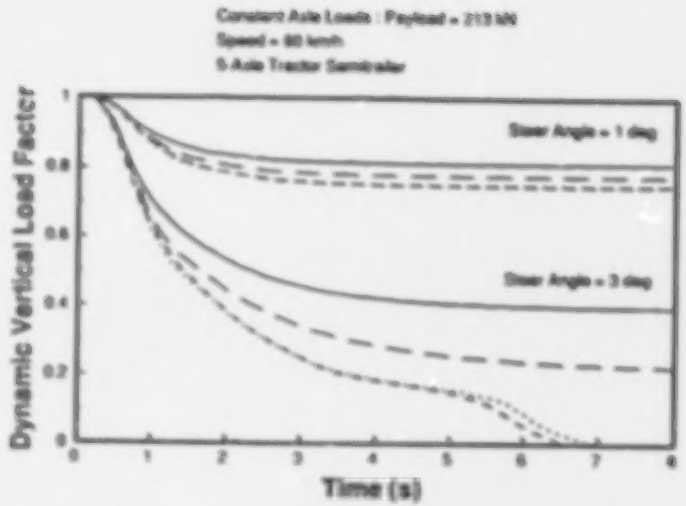

Constant Axle Loads : Payload = 213 kN
Speed = 80 km/h
5-Axle Tractor Semitrailer
Dynamic Vertical Load Factor
Time (s)
Steer Angle = 1 deg
Steer Angle = 3 deg

Figure 5.4: Dynamic vertical load factor on the inner track of trailer's rearmost axle.

60 km/h. The 40%- and 70%- filled tank semitrailers experience similar roll angle and lateral acceleration response for such steer inputs. In the case of 3 degrees steer input, partially filled liquid tank vehicles approach unstable behaviour asymptotically, as observed from the rapid increase in lateral acceleration and roll angle response of the trailer. The equivalent rigid cargo vehicles, however, exhibit stable behaviour under identical conditions of fill level, vehicle speed and steer angle, while the axle loads are held constant. A comparison of the roll and lateral acceleration response characteristics of equivalent rigid cargo vehicles reveals improved directional stability limits for 40%- filled vehicle under constant axle loading conditions. This is attributed to low overall centre of gravity height of the 40%- filled rigid cargo vehicle. In case of liquid load, however, the 40%- filled tank vehicle yields reduced directional stability due to excessive lateral load transfer.

The magnitude of lateral load transfer during a directional manoeuvre can be expressed in terms of the dynamic vertical load factor, defined as the ratio of instantaneous vertical load on the inner or the outer track of a given axle to the static vertical load on that track. Figure 5.4 illustrates the dynamic vertical load factor for the inner track of the rearmost semitrailer axle for 40%- and 70%- fill level for 1 and 3 degrees steady steer inputs. The dynamic load factor corresponding to the rigid cargo vehicle approaches a steady state value for both the steer inputs. Partially filled liquid tank vehicles also exhibit stable behaviour at small steer input (1 degree) and the corresponding dynamic load factor reaches a steady state value. The magnitude of dynamic load transfer, however, is larger than that of rigid cargo vehicles. At larger steer inputs the dynamic load factor of liquid tank vehicles quickly approaches zero indicating wheel lift-off, as shown in Figure 5.4. Although overall c.g. height of 40%- filled vehicle is considerably lower than that of the 70%- filled vehicle, excessive load transfer within 40%-filled vehicle results in an earlier wheel lift-off. The 40%- filled tank vehicle experiences a wheel lift-off around 6.5 seconds in comparison to 7 seconds for a 70%- fill level.

Directional response characteristics of commercial vehicles are strongly influenced by vehicle speed. Figure 5.5 presents the sprung mass roll angle response of partially filled liquid and rigid cargo semitrailers for a 1.5 degrees steady steer input at a speed of 90 km/h. An increase in vehicle speed affects the vehicle dynamic response adversely, leading to sharp increase in roll angle, as shown in Figure 5.5. The 40%- and 70%- filled tank vehicles experience large roll angle almost leading to rollover after 4 s. The 70%- filled equivalent rigid cargo vehicle also experiences a rollover near 6 s while the 40%- filled rigid cargo vehicle exhibits stable behaviour due to low overall c.g. height.

Six-Axle Tractor-Semitrailer (Three-axle semitrailer)

Computer simulations are performed to investigate the directional response of partially filled six-axle tractor-semitrailer tank vehicle subjected to steady steer inputs. The axle loads are held constant around the maximum permissible values (tractor's front axle: 55 kN, tractor's rear axle group: 170 kN, trailer axle group: 240 kN). Figure 5.6 presents the directional response characteristics of 40%- and 70%- filled liquid and

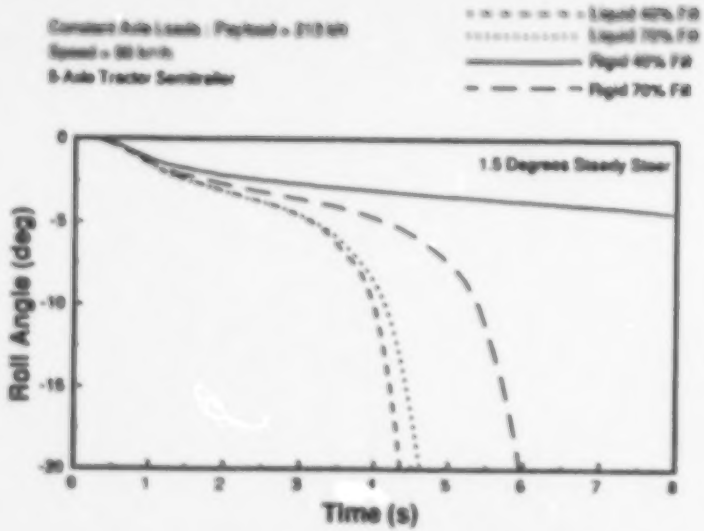


Figure 5.5: Roll response of semitrailer with liquid and equivalent rigid cargo at 90 km/h.

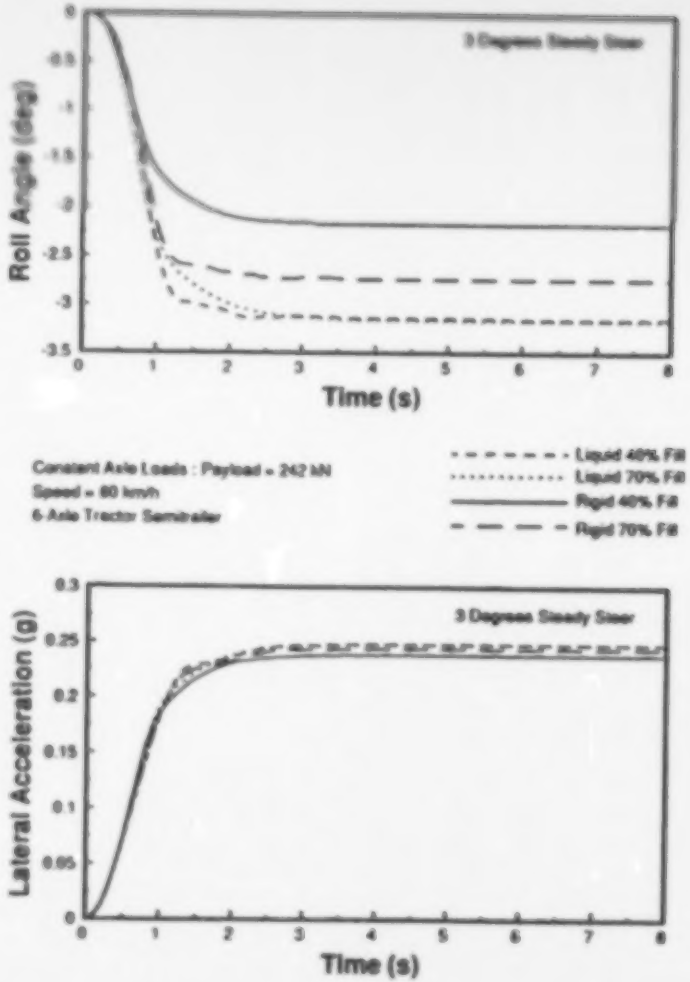


Figure 5.6: Transient directional response of semitrailer with liquid and equivalent rigid cargo.

equivalent rigid cargo vehicles with constant axle loads, for a steady steer input of 3 degrees. Although, overall c.g. height of 40%- filled liquid tank is considerably lower than that of the 70%- filled tank, the 40%- and 70%-filled tank vehicles experience similar roll and lateral acceleration response. The equivalent rigid cargo vehicles exhibit stable behaviour under identical conditions of fill level, vehicle speed and steer angle. A comparison of Figures 5.3 and 5.6 reveals that dynamic stability limits of a partially filled six-axle tank vehicle are considerably larger than that of a five-axle vehicle.

Seven-axle Tractor-Semitrailer (Four-axle semitrailer)

The directional response characteristics of a seven-axle tractor-semitrailer are evaluated for various fill levels, while the axle loads are held constant around the permissible values (tractor's front axle: 55 kN; tractor's rear axle group: 170 kN; trailer axle group: 304 kN) Figures 5.7 presents the directional response characteristics of 40% and 70%-filled seven-axle tractor-tank-semitrailer under constant axle loads subjected to steady steer input of 2 degrees. The 40% and 70%-filled equivalent rigid cargo vehicles indicate a stable response while liquid tank vehicles quickly approach rollover. The roll angle response of a 70%-filled rigid cargo vehicle however, continues to increase at a slower rate indicating that it may approach rollover.

Figure 5.8 illustrates a comparison of peak roll angle and lateral acceleration response of a liquid and a rigid cargo vehicle for various fill levels when the vehicles are subjected to a 1 degree constant steer input at a speed of 50 km/h. Under constant axle loads, higher density liquids decrease the fill level and thus, the overall c.g. height. The peak response of an equivalent rigid cargo vehicle then decreases with low fill levels. In the case of a liquid tank vehicle, however, the dynamic load transfer increases with reduced fill level and the corresponding peak response values increase. The peak roll angle and lateral acceleration response of a partially filled four-axle semitrailer is identical to that of a 100%-filled vehicle, as shown in Figure 5.8. Table 5.1 summarizes the directional response characteristics of partially filled five-, six- and seven-axle tractor-semitrailer tank vehicles, subjected to 3 degrees steer input.

5.5.2 TRANSIENT STEER MANOEUVRES

Computer simulations are performed to study the directional performance of partially filled tank vehicles equipped with cleanbore cylindrical tank subjected to transient steer manoeuvres such as lane change and evasive manoeuvres as shown in Figure 5.9. Directional response characteristics of five-, six- and seven-axle liquid and rigid cargo tractor-semitrailers are evaluated using a closed-loop path follower model [30]. The front wheel steer angles required to follow the prescribed path are computed using the closed-loop driver model and are presented in Figure 5.10. Fill levels of 40% and 70%, corresponding to vehicles carrying industrial acid (weight density = 0.0186 N/cm^3 or 0.0673 lb/in^3) and diesel oil (weight density = 0.0092 N/cm^3 or 0.034 lb/in^3), are considered.

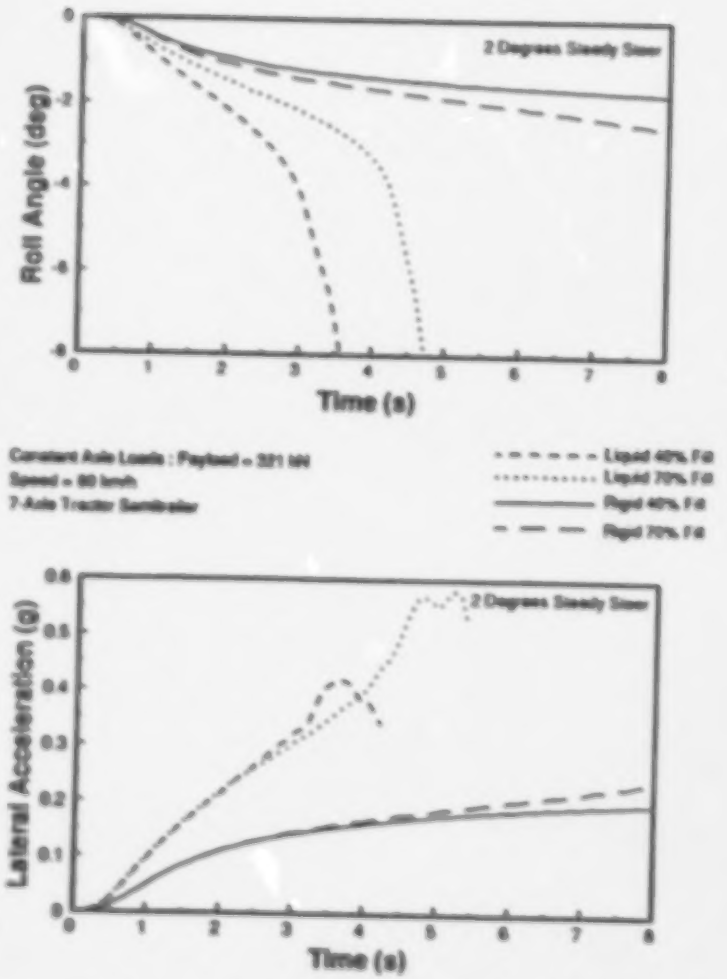


Figure 5.7: Transient directional response of semitrailer with liquid and equivalent rigid cargo.

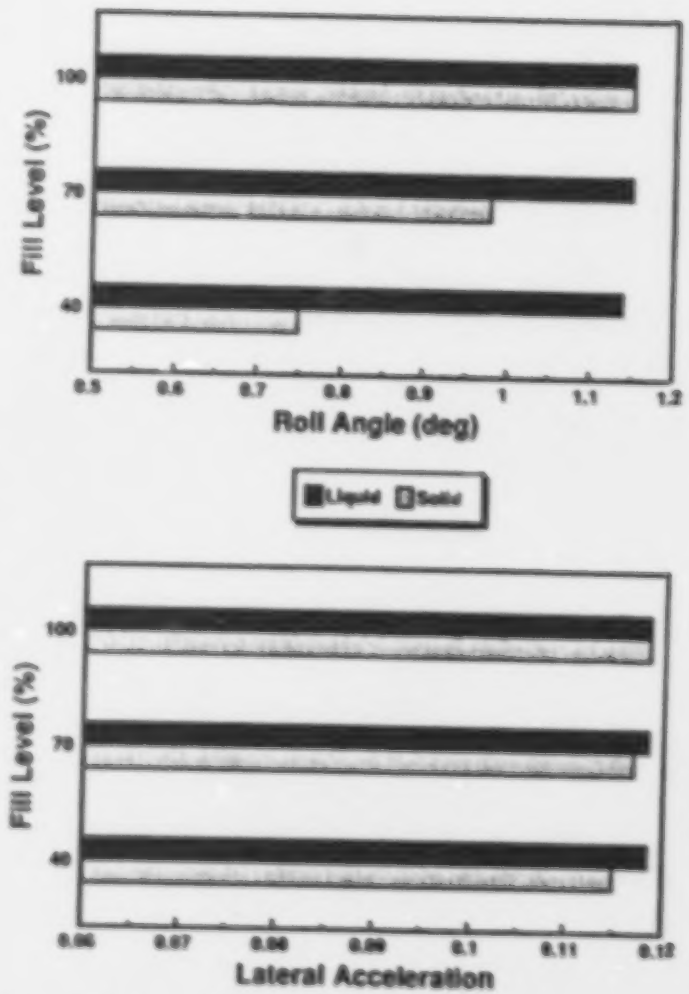


Figure 5.8: Comparison of peak response of semitrailer (Vehicle: 7-axle tractor-semitrailer).

TABLE 5.1
COMPARISON OF DIRECTIONAL RESPONSE CHARACTERISTICS OF TRACTOR SEMITRAILER TANK VEHICLES

Constant Steer Input : Steer Angle = 1° - Right Turn

Constant Axle Loads
Cargo Load : 5-Axle Tractor-Semitrailer : 213 kN (47930 lb)
6-Axle Tractor-Semitrailer : 242 kN (54440 lb)
7-Axle Tractor-Semitrailer : 321 kN (72130 lb)

Response Parameter	Vehicle Configuration		
	Five-Axle	Six-Axle	Seven-Axle
Load Shift	Peak Values of Response Parameters		
$Y_{\ell 2}$	-15 cm; unstable	-9.2 cm	-25.4 cm; unstable
$Z_{\ell 2}$	5 cm; unstable	0.81 cm	6.3 cm; unstable
Roll Angle			
Rigid	-2.4°	-1.26°	-1.23°
Liquid	-14.0°; unstable	-1.88°	-6.0°; unstable
Lateral Acceleration			
Rigid	0.24g	0.14g	0.18g
Liquid	0.40g; unstable	0.15g	0.35g; unstable
Yaw Rate			
Rigid	5.2 deg/s	3.1 deg/s	6.1 deg/s
Liquid	9.3 deg/s; unstable	3.3 deg/s	12 deg/s; unstable
Roll Rate			
Rigid	-1.8 deg/s	-1.54 deg	-0.58 deg/s
Liquid	-2.1 deg/s; unstable	-2.18 deg	-2.4 deg/s; unstable

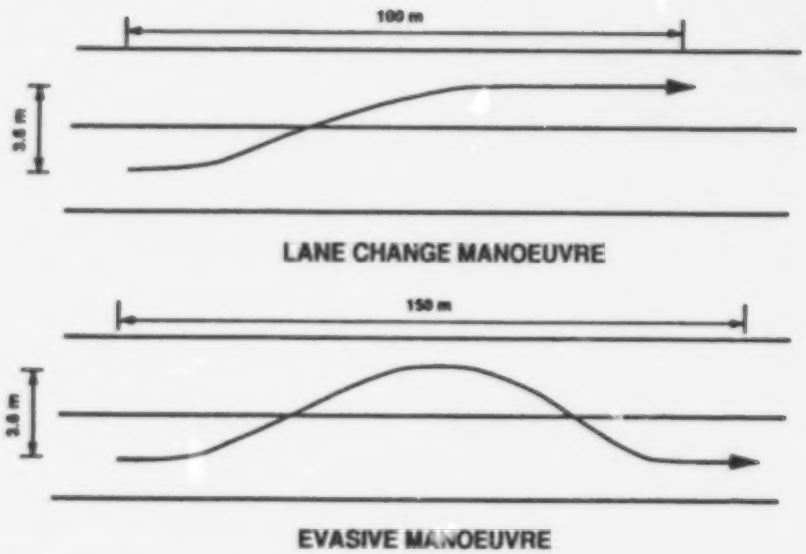


Figure 5.9: Vehicle path during typical lane change and evasive manoeuvres.

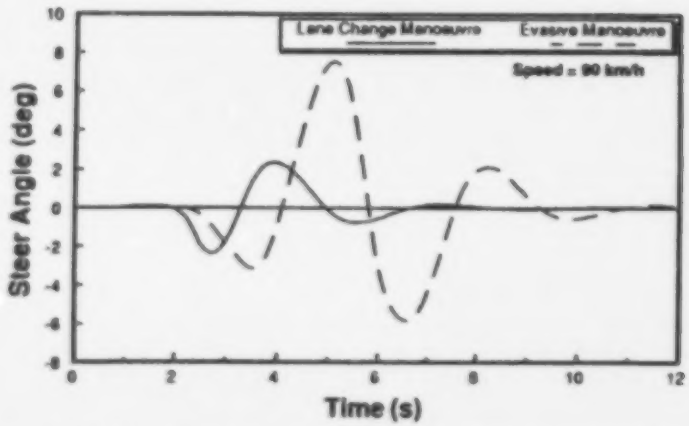


Figure 5.10: Front wheel steer angles required to perform typical lane change and evasive manoeuvres.

Five-Axle Tractor-Semitrailer (Two-axle semitrailer)

The directional response of a five-axle tank vehicle is investigated for 40% and 70%-fill conditions while the axle loads are held around the maximum permissible values. The roll angle response for lane change and evasive manoeuvres at 90 km/h, is presented in Figure 5.11. During a lane change manoeuvre the liquid and equivalent rigid cargo trailers exhibit stable response. The increase in liquid load shift within the partially filled tank, however, increases the roll response of a liquid cargo vehicle. During an evasive manoeuvre the 70%-filled five-axle tank-semitrailer vehicle rolls over immediately after the steering input is applied, while the equivalent rigid cargo vehicle exhibits wheel lift off (Fig. 5.12).

Figure 5.12 presents the vertical load on the left and right tracks of the rearmost semitrailer axle during an evasive manoeuvre. The right track load of the 70%-filled equivalent rigid cargo vehicle approaches zero at 5 s indicating wheel lift-off. The wheel-road contact is regained when steer direction is reversed as shown in Figure 5.12. The 40%-filled liquid cargo vehicle also exhibits right and left wheels lift-off around 5 s and 6.8 s respectively, after the steer input is applied. Wheel-road contact is regained when the steer directions are reversed, as shown in Figure 5.12. The 70%-filled liquid tank vehicle experiences right wheel lift-off near 5 s and rolls over.

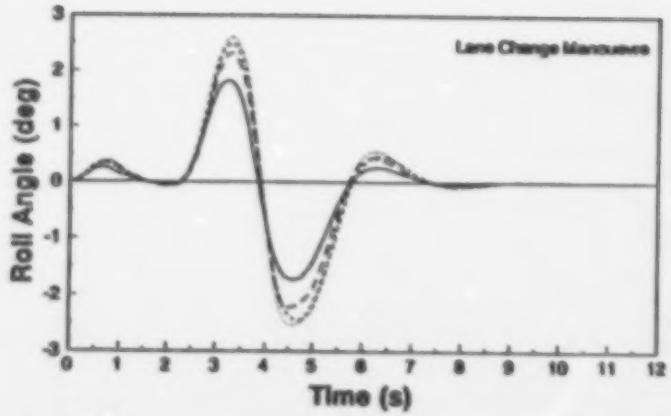
Six-Axle Tractor-Semitrailer (Three-axle semitrailer)

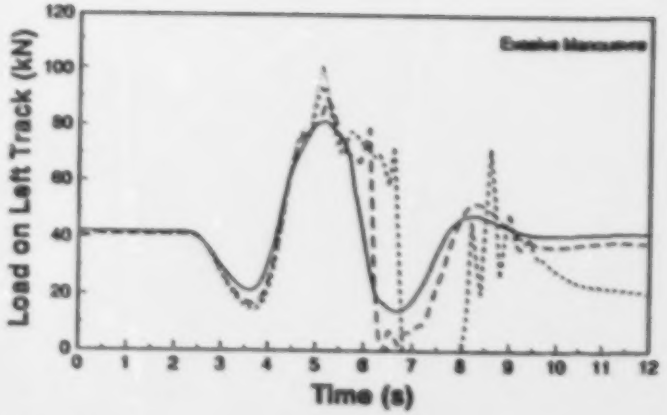
The directional response of a partially filled six-axle tractor-semitrailer tank vehicle is investigated for lane change and evasive manoeuvres. Figure 5.13 presents a comparison of the roll angle and lateral acceleration response of 40% and 70%-filled liquid tank and the equivalent rigid cargo trailers when both the vehicles are subjected to a lane change manoeuvre at a speed of 90 km/h. The lateral load shift within the partially filled tank trailer leads to larger roll compared to that of the equivalent rigid cargo trailer, as shown in Figure 5.13. The lateral acceleration response, however, shows very little deviation between the liquid and rigid cargo trailers.

The roll response characteristics of 40% and 70%-filled six-axle tank vehicles are compared to those of the equivalent rigid cargo vehicles when both the vehicles are subjected to an evasive manoeuvre as shown in Figure 5.14. The 70%-filled liquid tank trailer experiences approximately 2.5 degrees more roll than the equivalent rigid cargo trailer under identical vehicle speed and axle loading conditions. A comparison of Figures 5.11 and 5.14 clearly reveals that the six-axle tractor-tank-semitrailer is more stable compared to the five-axle tractor-tank-semitrailer when both vehicles carry the maximum permissible loads.

Seven-Axle Tractor-Semitrailer (Four-axle semitrailer)

Figure 5.15 presents the roll angle and lateral acceleration response characteristics of 40% and 70%-filled seven-axle tractor-semitrailer subjected to a lane change manoeuvre at a speed of 90 km/h under constant axle loading conditions. The increase in liquid load shift within a 40%-filled





Constant Axle Loads : Payload = 213 kN
Speed = 90 km/h
5-Axle Tractor Semitrailer

Liquid 40% Fill
Liquid 70% Fill
Rigid 40% Fill
Rigid 70% Fill

Constant Axle Loads : Payload = 213 kN
Speed = 90 km/h
5-Axle Tractor Semitrailer

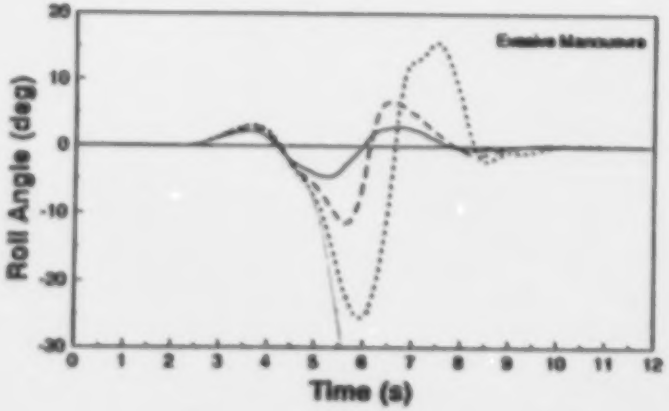


Figure 5.11: Roll response of semitrailer with liquid and equivalent rigid cargo during transient manoeuvres.

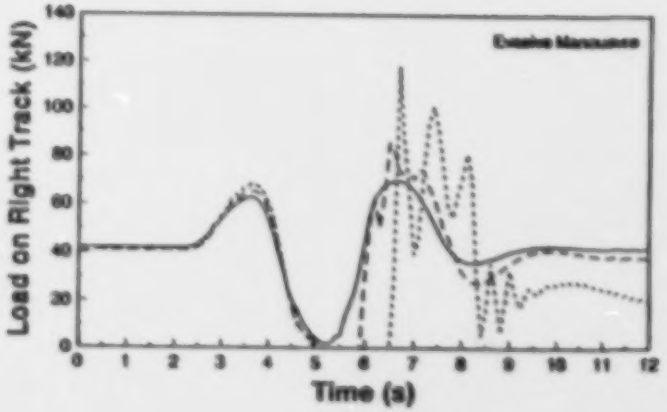


Figure 5.12: Vertical load on trailer's rearmost axle.

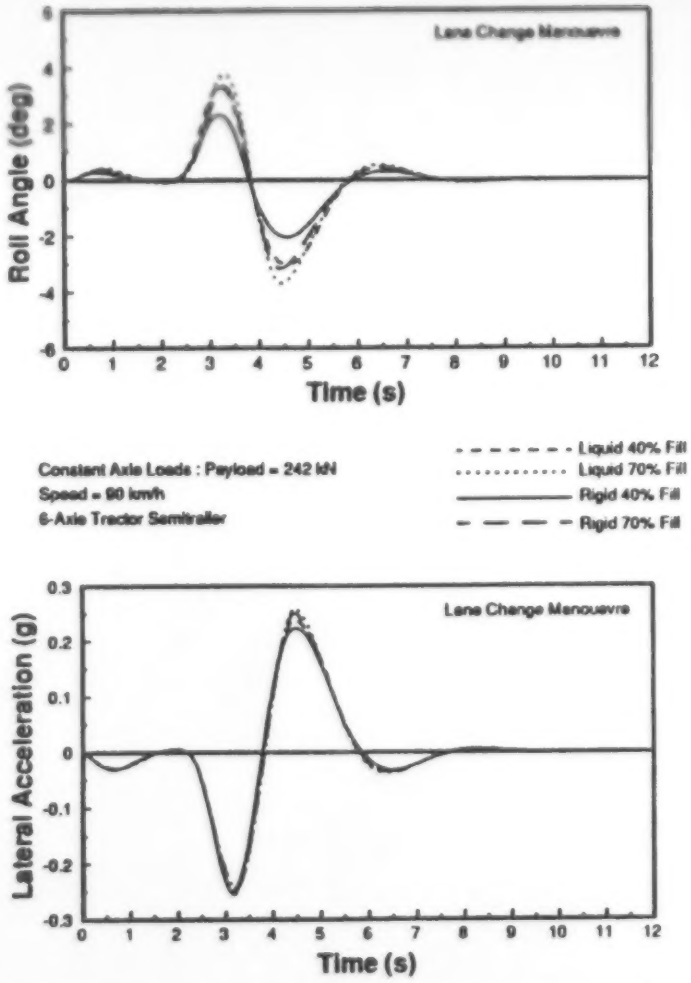


Figure 5.13: Transient directional response of semitrailer with liquid and equivalent rigid cargo.

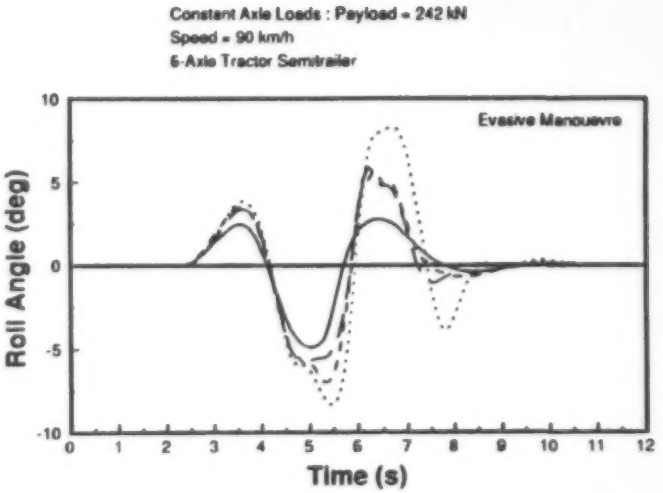
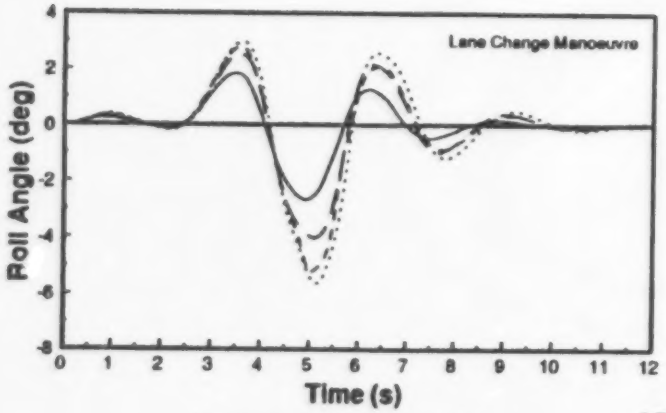
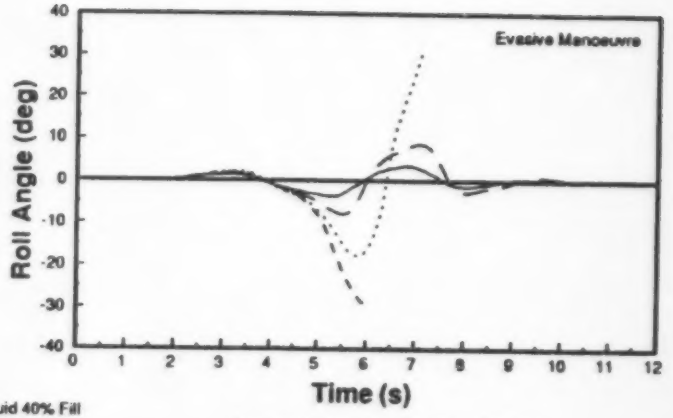
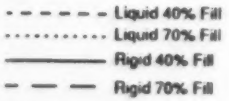
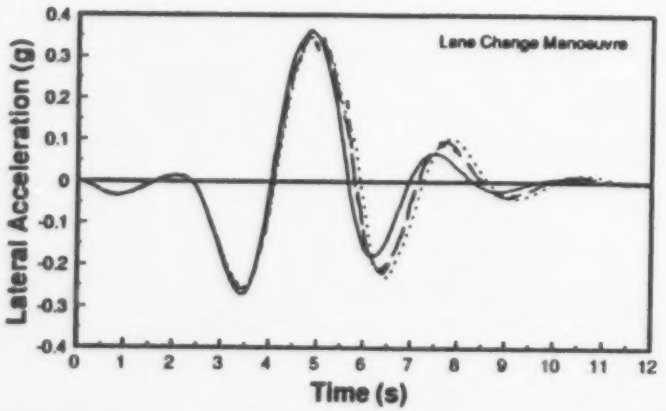


Figure 5.14: Roll response of semitrailer with liquid and equivalent rigid cargo during an evasive manoeuvre.









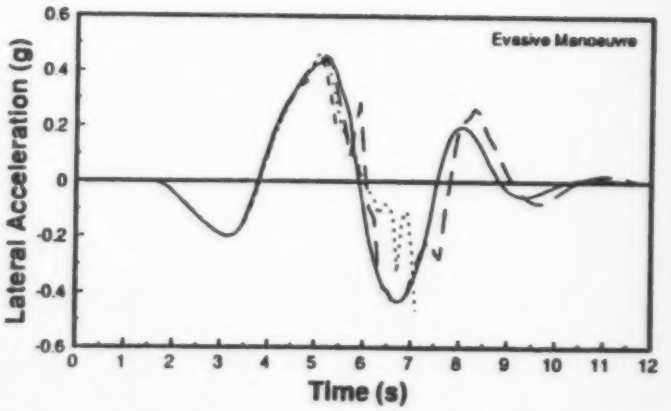


Figure 5.15: Transient directional response of semitrailer with liquid and equivalent rigid cargo.

Figure 5.16: Transient directional response of semitrailer with liquid and equivalent rigid cargo.

tank-trailer increases the roll angle response close to that of a 70%-filled tank trailer. The 40%-filled equivalent rigid cargo trailer, however, exhibits a lower roll response due to a lower c.g. height. Figure 5.16 presents the roll angle and lateral acceleration response of liquid and equivalent rigid cargo vehicles subjected to an evasive manoeuvre at a speed of 70 km/h. The transient roll angle response clearly illustrates that 40% and 70% filled vehicles quickly approach rollover while the equivalent rigid cargo vehicles remain directionally stable. Table 5.2 presents a comparison of the directional response characteristics of five-, six- and seven-axle tractor-semitrailer tank vehicles subjected to an evasive manoeuvre under constant axle loading conditions.

5.6 Directional Response of a B-Train with Cleanbore Cylindrical Tanks

Directional response of a 7-axle B-train tank vehicle equipped with cleanbore cylindrical tanks is investigated for constant and transient steer manoeuvres while the axle loads are held constant. The directional response characteristics are presented in terms of transient roll angle, roll rate and lateral acceleration of the sprung mass of the partially filled rear trailer.

5.6.1 CONSTANT STEER MANOEUVRES

Computer simulations are performed to determine the directional dynamics of a 7-axle B-Train equipped with circular cross-section tanks for steady steer inputs. Payloads carried by the two semitrailers are held constant at a value that corresponds to fully loaded tanks carrying fuel oil of weight density = 0.0068 N/cm^3 (0.025 lb/in^3). The fill levels vary with variations in the weight density of liquid cargo being transported. Computer simulations are carried out to investigate the directional response characteristics of the B-Train tank vehicle carrying following types of cargo:

Industrial Acids : Weight Density = 0.0136 N/cm^3 (0.05 lb/in^3)
Fill Level = 50%

Diesel Oils : Weight Density = 0.0084 N/cm^3 (0.031 lb/in^3)
Fill Level = 75%

Table 5.3 summarizes the specifications of the tank vehicle used in simulation.

Directional response characteristics of the rearmost semitrailer are computed for a constant steer input of 2 degrees and vehicle speed of 50 km/h. The roll angle, lateral acceleration and roll rate response characteristics of the 100% and 50%-filled rear trailers are compared to those of the equivalent rigid cargo trailers, as shown in Figure 5.17. The overall sprung mass c.g. height of the semitrailer decreases when the fill level is reduced. Consequently, the peak roll angle, and roll rate response of equivalent rigid cargo trailer decrease. The liquid load shift encountered due to partial fill in the tank, however, adversely influences the directional characteristics of the liquid cargo vehicle, as shown in Figure 5.17. The vehicle combination carrying rigid cargo equivalent to 50%-fill exhibits the lowest sprung mass roll and lateral acceleration, while the 100%-filled trailer exhibits the highest vehicle roll and lateral acceleration response. The 50%-filled liquid

TABLE 5.2
COMPARISON OF DIRECTIONAL RESPONSE CHARACTERISTICS OF TRACTOR SEMITRAILER TANK VEHICLES

Evasive Manoeuvre : Path Follower Model

Constant Axle Loads

Cargo Load : 5-Axle Tractor Semitrailer : 213 kN (47930 lb)
6-Axle Tractor Semitrailer : 242 kN (54440 lb)
7-Axle Tractor Semitrailer : 321 kN (72130 lb)

Response Parameter (peak)	Vehicle Configuration		
	Five-Axle	Six-Axle	Seven-Axle
Load Shift	Peak Values of Response Parameters		
$Y_{\ell 2}$	-18 cm; unstable	-16.3 cm	-20.3; unstable
$Z_{\ell 2}$	7.5 cm; unstable	7.2 cm	20; unstable
Roll Angle			
Rigid	-10.0°	-5.2°	-30.0°; unstable
Liquid	-30.0°; unstable	-7.2°	-30.0°; unstable
Lateral Acceleration			
Rigid	+0.48g	0.62g	-4.45g; unstable
Liquid	+0.51g; unstable	0.73g	-0.45g; unstable
Roll Rate			
Rigid	+38.0 deg/s (peak)	18.6 deg/s	-74 deg/s; unstable
Liquid	-33.0 deg/s; unstable	24.8 deg/s	-92 deg/s; unstable

TABLE 5.3

SPECIFICATIONS OF B-TRAIN TANK VEHICLE USED IN SIMULATION

Tractor	
Type:	Three Axle
Sprung Weight:	52486N (11800 lb)
Unsprung Weight (front axle):	5338N (1200 lb)
Unsprung Weight (rear axle):	11120N (2500 lb)
Front Axle Suspension Rating:	88960N (20000 lb)
Rear Axle Suspension Rating:	97856N (22000 lb)
Wheel Base:	4.42m (174 in)
Tare Centre of Gravity Height:	1.12m (44 in)
Roll Moment of Inertia:	2938 N.m.s^2 (26000 lb.in.s^2)
Yaw Moment of Inertia:	19207 N.m.s^2 (170000 lb.in.s^2)
Pitch Moment of Inertia:	19207 N.m.s^2 (170000 lb.in.s^2)
Semitrailer A	
Type:	Tandem Axle
Sprung Weight (Empty):	51828N (11652 lb)
Unsprung Weight:	13344N (3000 lb)
Tank Length:	7.85m (309 in)
Tank Diameter:	2.03m (80 in)
Axle Rating:	97856N (22000 lb)
Weight Density (Fuel Oil):	0.0068N/cm^3 (0.025lb/in^3)
Tare Centre of Gravity Height:	1.54m (60.79 in)
Roll Moment of Inertia:	9039 N.m.s^2 (80000 lb.in.s^2)
Yaw Moment of Inertia:	11298 N.m.s^2 (100000 lb.in.s^2)
Pitch Moment of Inertia:	11298 N.m.s^2 (100000 lb.in.s^2)
Semitrailer B (rear-most semitrailer)	
Type:	Tandem Axle
Sprung Weight (Empty):	38813N (8726 lb)
Unsprung Weight:	13344N (3000 lb)
Tank Length:	7.60m (299 in)
Tank Diameter:	2.03m (80 in)
Axle Rating:	97856N (22000 lb)
Tare Centre of Gravity Height:	1.54m (60.79 in)
Roll Moment of Inertia.	9039 N.m.s^2 (80000 lb.in.s^2)
Yaw Moment of Inertia:	11298 N.m.s^2 (100000 lb.in.s^2)
Pitch Moment of Inertia:	11298 N.m.s^2 (100000 lb.in.s^2)

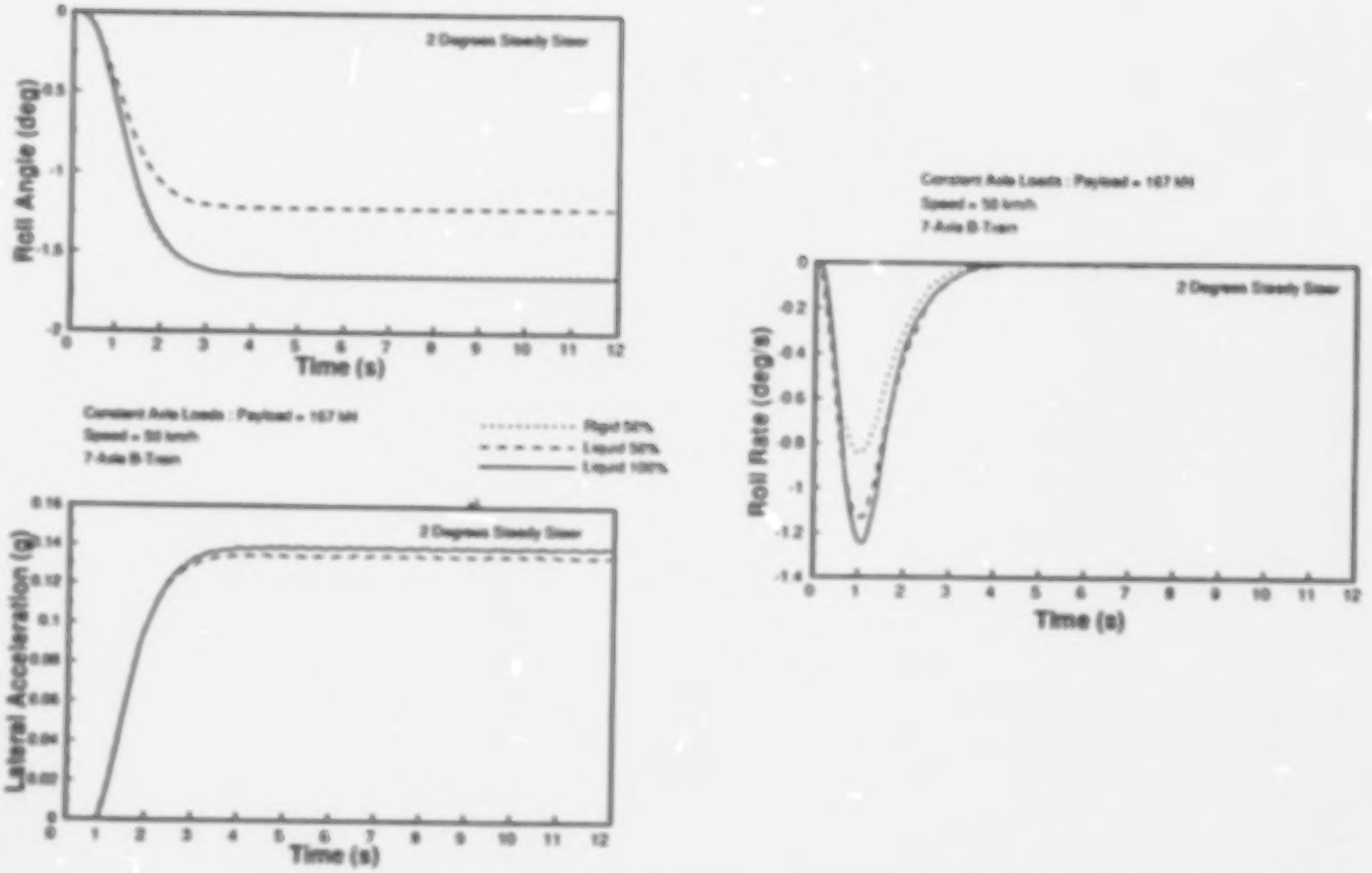


Figure 5.17: Transient directional response of rearmost semitrailer with liquid and equivalent rigid cargo.

cargo trailer, however, experiences dynamic response almost similar to that of a completely full trailer due to the associated slosh forces arising from the liquid load shift. The 100% and 50%-filled rearmost trailer of the B-Train experiences a steady state roll of approximately 1.65 degrees, while the trailer with rigid cargo equivalent to 50%-fill reaches a steady state roll angle of approximately 1.2 degrees.

The lateral acceleration response of the 50%-filled liquid trailer is almost identical to that of the completely full trailer under constant axle loading conditions. The peak roll rate corresponding to the completely full vehicle is approximately 1.28 deg/s compared to 1.18 deg/s in the case of the 50%-filled liquid tank vehicle and 0.8 deg/s in the case of the equivalent rigid cargo vehicle, as shown in Figure 5.17.

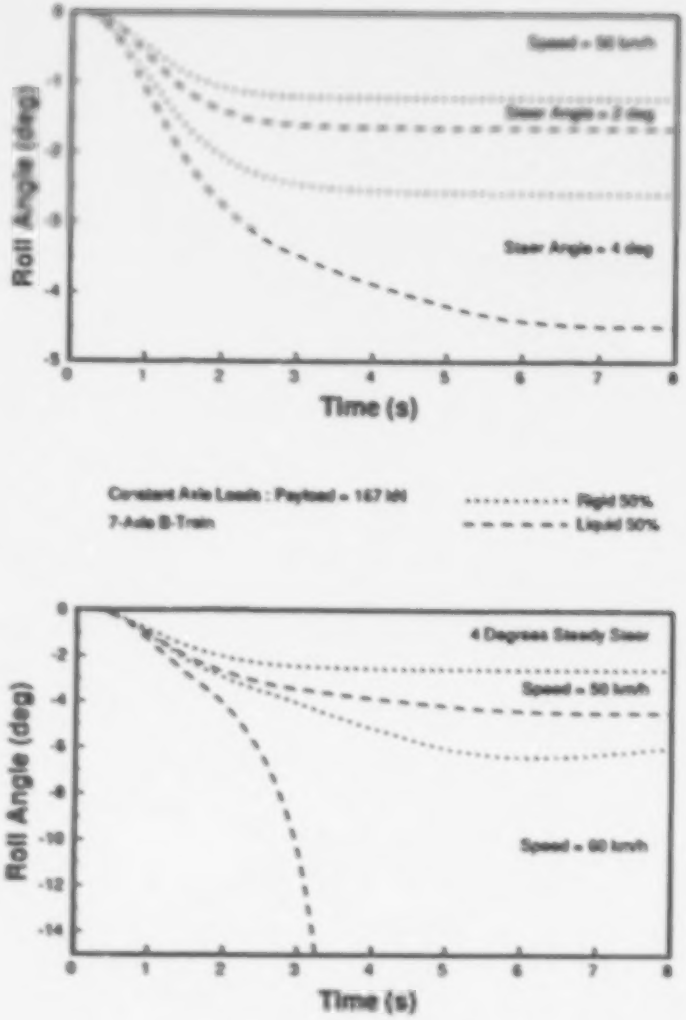
Roll response characteristics of the rearmost trailer are investigated for variations in fill level, steer angle and vehicle speed as illustrated in Figure 5.18. The roll response characteristics of the rearmost semitrailer carrying industrial acid (fill level = 50%) and diesel oil (fill level = 75%), are investigated for a 2 degree constant steer input. The total payload is held constant for both. In the case of rigid cargo vehicles, the rigid cargo equivalent to 75%-fill yields considerably larger roll than that equivalent to 50%-fill due to increased c.g. height. Although the c.g. height of the 50%-filled tank vehicle is considerably lower than that of the 75%-filled tank vehicle, the roll response of the two vehicles is identical. This is attributed to the increased lateral load shift within a 50%-filled tank.

Figure 5.18 also presents the roll angle response of the rearmost trailer for variation in the steer angle. A comparison of roll angle response of liquid and equivalent rigid cargo vehicles subjected to 2 degrees constant steer input, reveals that the liquid tank vehicle experiences approximately 0.5 degree more roll and the difference in the roll response is approximately 2 degrees when the vehicle is subjected to a constant steer of 4 degrees. The influence of vehicle speed is also illustrated in Figure 5.18. A comparison of roll response characteristics of the rear trailer with 50%-filled liquid and equivalent rigid cargo at a vehicle speed of 50 km/h and 4 degrees steady steer, reveals that the liquid tank vehicle experiences approximately 2 degrees higher roll. The partially filled liquid tank vehicle, however, exhibits rollover when the vehicle speed is increased to 60 km/h while the rigid cargo vehicle exhibits a stable roll response.

Unequal distribution of vertical load on the inner and outer track arising from the lateral load shift, increases the cornering forces at the outer track of the vehicle leading to considerable deviation in the path of the tank vehicle. Figure 5.19 presents the trajectories of the path followed by the 50%-filled liquid and rigid cargo vehicles, subjected to 4 degrees constant steer input at 50 km/h. A comparison of the paths followed by liquid and rigid cargo vehicles reveals that the magnitude of path deviation diverges with time. The path followed by the tank vehicle deviates approximately 10 m from that of the rigid cargo vehicle at the end of 12 seconds.

5.6.2 TRANSIENT STEER MANOEUVRES

The directional response characteristics of B-train tank vehicle are



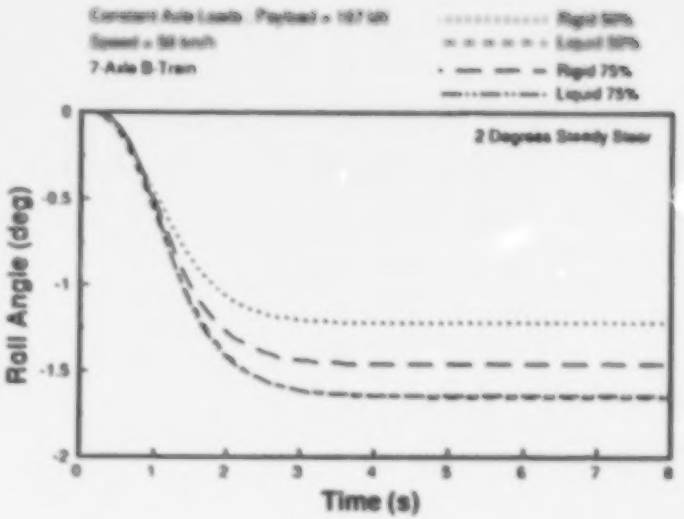


Figure 5.18: Influence of vehicle speed, steer angle and fill level on the roll response of the rearmost semitrailer.

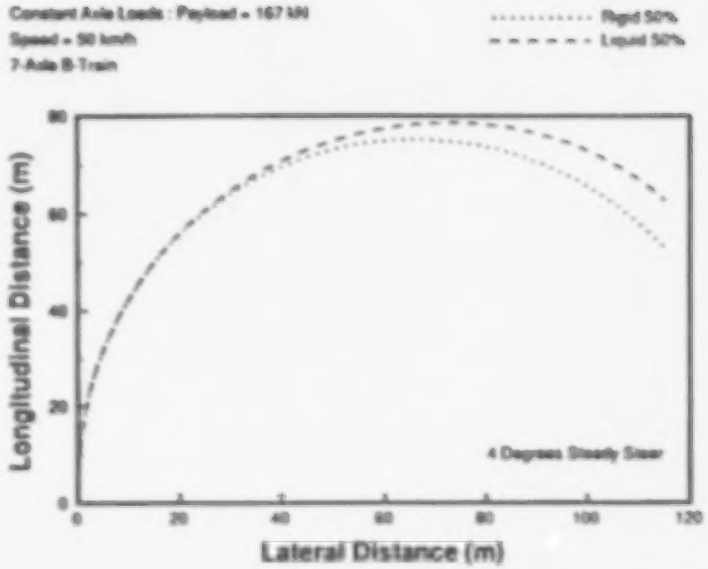


Figure 5.19: Comparison of vehicle path followed by liquid and equivalent rigid cargo B-train vehicles.

evaluated for a 3.6 m (12 feet) lane change manoeuvre executed at a constant speed of 80 km/h. Roll angle and lateral acceleration response characteristics of the rearmost semitrailer are presented in Figure 5.20. Fill level in the cleanbore tanks is varied by changing the weight density of liquid cargo such that the axle loads are held constant. Roll angle and lateral acceleration response characteristics of the 50%-filled rearmost liquid trailer are compared to those of an equivalent rigid cargo and completely filled trailer as shown in Figure 5.20. The peak roll angle response of 50%-filled equivalent rigid cargo trailer is considerably smaller than that of the 100%-filled tank trailer, due to a lower c.g. height. The peak roll response of the 50%-filled liquid trailer, however, approaches that of the 100%-filled trailer due to associated liquid load shift. The peak values of lateral acceleration response of liquid and rigid cargo trailers are observed to be almost identical during the lane change manoeuvre. The lateral acceleration response of the 50%-filled liquid tank trailer, during the correction phase of the lane change manoeuvre, is however, approximately 0.03 g higher than that of the equivalent rigid cargo trailer and is comparable to that of fully loaded tank trailer.

Figure 5.21 presents the roll response of a 50%-filled rearmost trailer when the vehicle is negotiating a lane change manoeuvre at 70 and 80 km/h. The peak roll angle increases from 2.5 degrees to 3.5 degrees when the speed is increased from 70 to 80 km/h, while for a rigid cargo trailer it increases by only 0.5 degrees.

The directional performance of B-train tank vehicle combination is also investigated for an evasive or double lane change manoeuvre as a function of fill level and vehicle speed. The variations in fill level are realized by varying weight density of the liquid cargo in order to retain constant axle loads. Roll angle and lateral acceleration response characteristics of the partially filled (50%) rearmost trailer are compared to those of an equivalent rigid cargo trailer and 100%-filled trailer under identical axle loads, as shown in Figure 5.22. Peak roll angle response of the rearmost trailer of a partially filled liquid tank vehicle is observed to be twice as large as that of the equivalent rigid cargo vehicle, when the vehicle makes the first lane change. The peak roll angle for the partially filled liquid trailer is, however, almost identical to that of the 100%-filled trailer. The lateral acceleration response of 50%- and 100%-filled liquid tank vehicles exhibit sudden fluctuations due to wheel lift-off encountered during the manoeuvre, while the 50%-filled rigid cargo vehicle exhibits a stable response.

The influence of vehicle speed on the directional response of B-train tank vehicles during an evasive manoeuvre, is presented in Figure 5.23. A partially filled B-train tank vehicle experiences rollover when vehicle speed is increased to 80 km/h, while the rigid cargo vehicle remains directionally stable.

5.6.3 ROLL AND LATERAL ACCELERATION AMPLIFICATION

The impending rollover caused by directional instabilities originating at the rearmost trailer is often not felt by the driver. The transient directional response of the rearmost trailer, in general, may change markedly without any detectable change in the directional response of the tractor. The

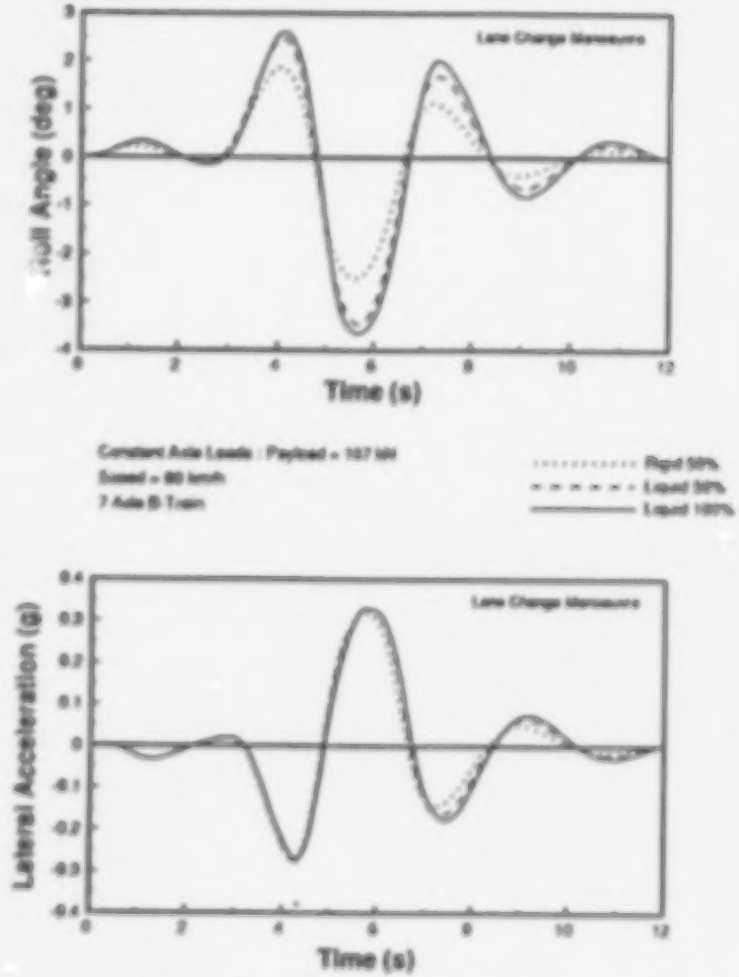


Figure 5.20: Transient directional response of rearmost semitrailer with liquid and equivalent rigid cargo.

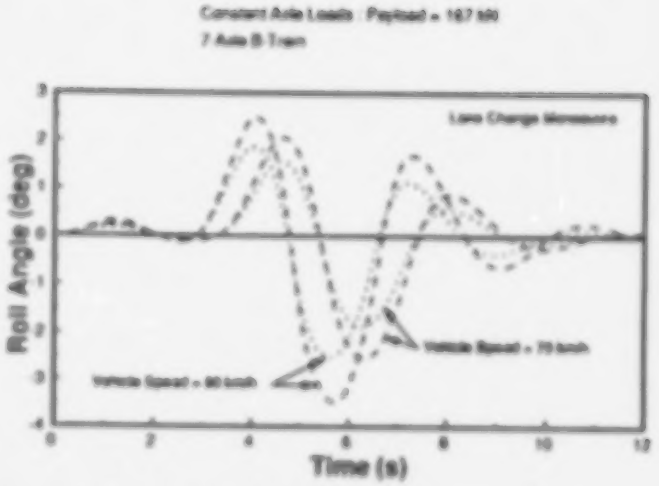

Constant Axle Loads : Payload = 167 kN
7 Axle B-Train
Lane Change Manoeuvre
Roll Angle (deg)
Vehicle Speed = 80 km/h
Vehicle Speed = 70 km/h
Time (s)

Figure 5.21: Roll angle response of rearmost semitrailer with liquid and equivalent rigid cargo at various vehicle speeds.

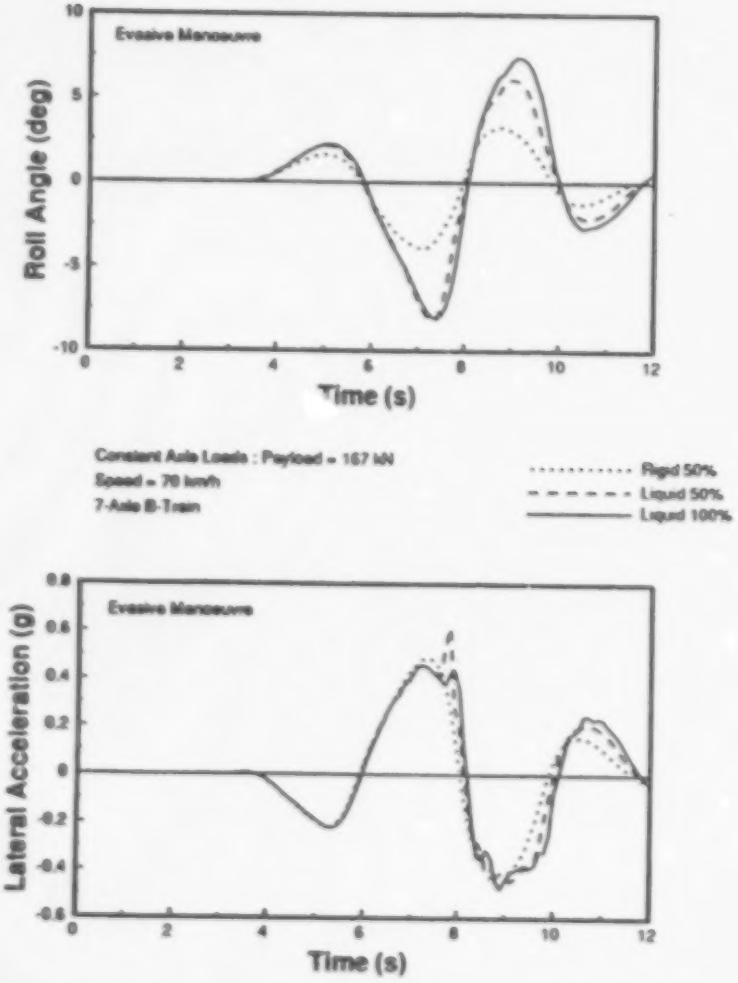


Figure 5.22: Transient directional response of rearmost semitrailer with liquid and equivalent rigid cargo.

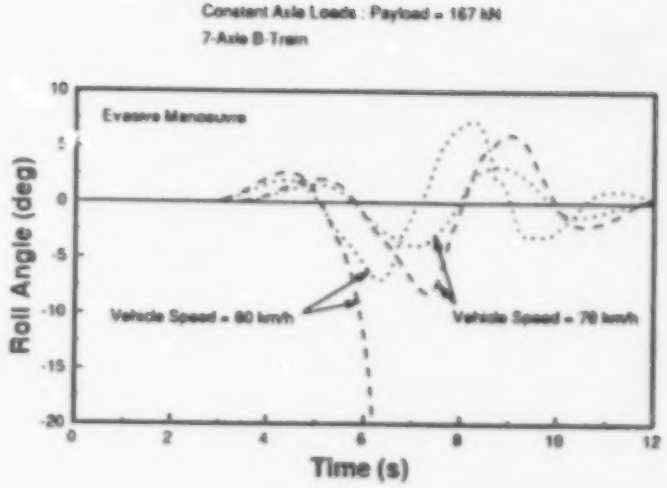


Figure 5.23: Roll angle response of rearmost semitrailer with liquid and equivalent rigid cargo at various vehicle speeds.

ratio of directional response parameters of the rearmost trailer to those of the tractor are often referred to as the amplification factors. The roll and lateral acceleration amplification factors define the severity of impending rollover of the trailers and are computed as follows:

$$A_\theta = \frac{\text{peak roll angle response of rearmost trailer } \theta_{s3}}{\text{peak roll angle response of tractor } \theta_{s1}} \qquad (5.16)$$

$$A_a = \frac{\text{Peak lateral acceleration response of the rearmost trailer } a_3}{\text{peak lateral acceleration response of the tractor } a_1} \qquad (5.17)$$

where A_θ and A_a are the roll angle and lateral acceleration amplification factors, respectively. Table 5.4 summarizes the roll and lateral acceleration amplification factors of a B-Train during lane change and evasive manoeuvres at various vehicle speeds. The amplification factors for the 50%-filled rigid cargo vehicle are observed to be low, while the 50%-filled liquid cargo vehicle experiences higher amplification of the dynamic response parameters. During a lane change manoeuvre, the partially filled liquid tank vehicle exhibits amplification factors very close to the 100%-filled vehicle due to increased liquid load shift and roll moments.

5.7 Directional Dynamics of Compartmented Tractor-Tank-Semitrailers

Cleanbore cylindrical tanks, employed in general purpose chemical fleet, often carry partial loads due to variations in weight density. Tank vehicles, employed in transportation of fuel oils, carry partial loads during their delivery routes. Modified-oval cross-section compartmented tanks are often used in transportation of fuel oils to avoid partial filling and to carry different types of fuel oils. Directional response characteristics of such vehicles are investigated for steady as well as transient steering manoeuvres to study the stability limits of compartmented tank vehicles. A four-compartment five-axle tractor-tank-semitrailer with smaller mid-compartments (capacity: 6000 ℓ) and larger end compartments (capacity: 12000 ℓ) is selected for this study.

5.7.1 STEADY STEER MANOEUVRES

Computer simulations are performed with a 1 degree steady steer input at a speed of 50 km/h with one of the compartments being empty. Payload and thus the axle loads vary in each simulation run due to different compartment sizes. Payload, axle loads and overall centre of gravity height of the tank vehicle with an empty mid-compartment are considerably larger than those of the vehicle with an empty end compartment. The peak roll angle of a vehicle with an empty mid-compartment is larger than the one with an empty end-compartment, as shown in Figure 5.24. The corresponding peak lateral acceleration response is marginally less than that experienced by the vehicle with an empty end-compartment. It is interesting to note that the peak lateral acceleration response of the tank vehicle with an empty end compartment is observed to be larger than that experienced by a fully loaded vehicle.

TABLE 5.4
ROLL AND LATERAL ACCELERATION AMPLIFICATION FACTORS DURING LANE CHANGE AND EVASIVE MANOEUVRES

Manoeuvre	Speed km/h	Amp. Factor	Fill Level				
			Full 100%	Liquid 50%	Rigid 50%	Liquid 75%	Rigid 75%
Evasive	70	A_θ	1.27	1.23	1.21	1.27	1.27
		A_a	1.96	1.87	1.64	1.94	1.83
	80	A_θ	•	•	1.31	•	•
		A_a	•	•	1.57	•	•
Lane Change	70	A_θ	1.21	1.22	1.17	1.21	1.19
		A_a	1.44	1.41	1.35	1.44	1.42
	80	A_θ	1.23	1.23	1.20	1.23	1.21
		A_a	1.64	1.62	1.56	1.64	1.62

• INDICATES ROLLOVER

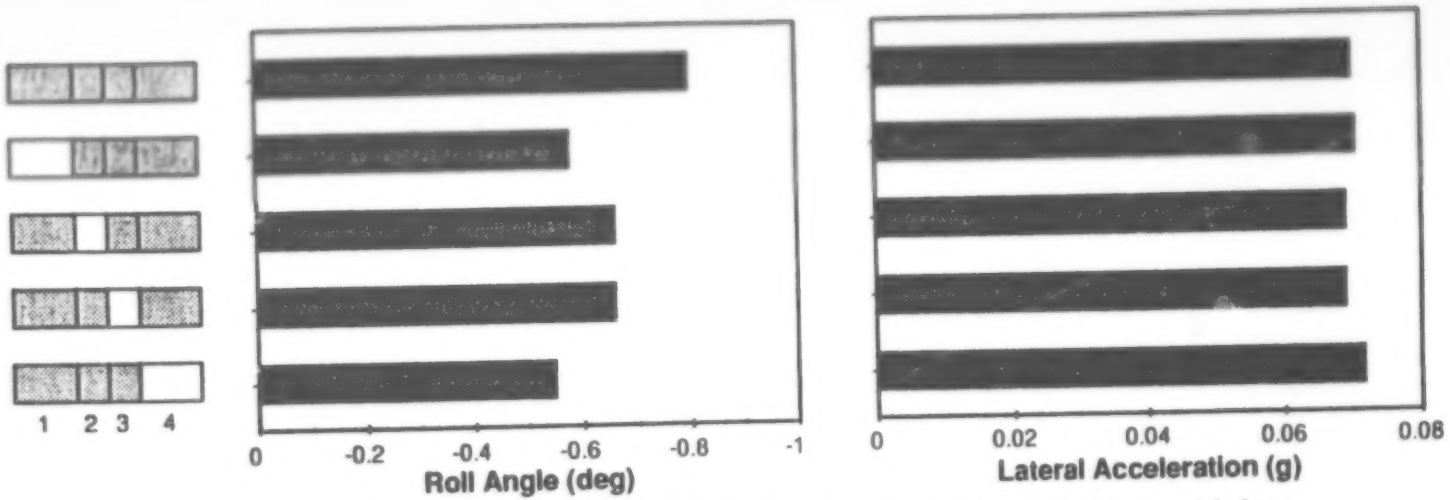


Figure 5.24: Influence of location of an empty compartment on vehicle response (Vehicle: 5-axle tractor-semitrailer).

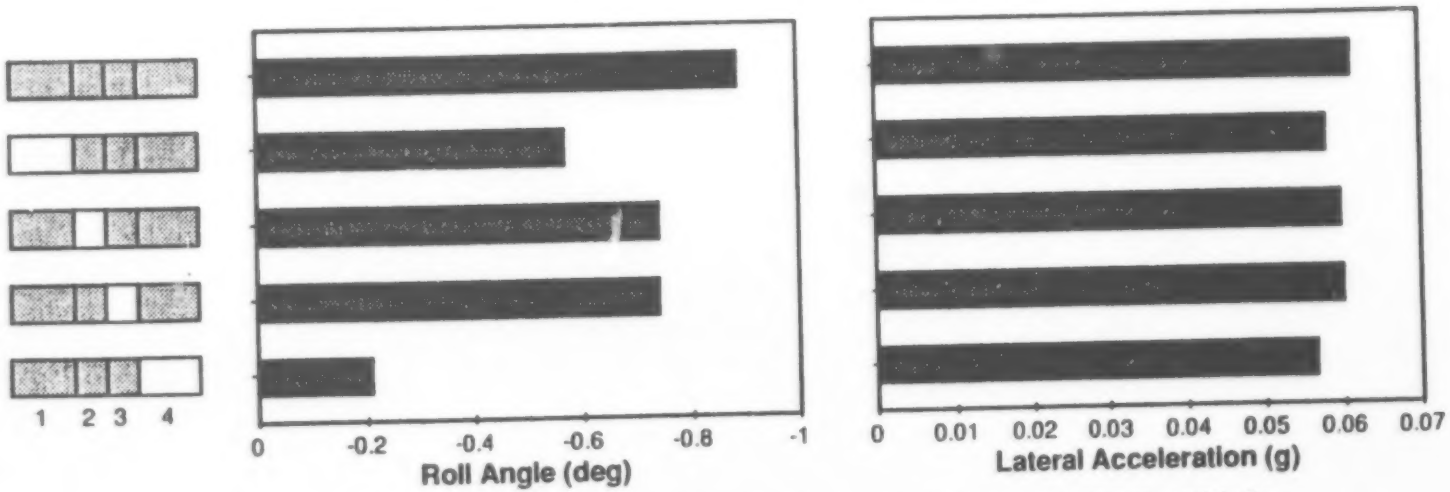


Figure 5.25: Influence of location of an empty compartment on vehicle response (Vehicle: 6-axle tractor-semitrailer).

Figure 5.25 presents a comparison of the peak roll angle and lateral acceleration response of a four-compartment six-axle tractor-tank-semitrailer vehicle with one empty compartment, subjected to 1 degrees steady steer at a speed of 50 km/h. The peak response characteristics are quite similar to those of the five-axle vehicle. The tank vehicle with an empty rearmost compartment yields considerably lower roll angle and lateral acceleration, while the trailer with an empty mid-compartment exhibits high roll as well as lateral acceleration. Lower values of roll angle and lateral acceleration response for empty rear compartment are attributed to reduced payload, c.g. height and load on trailer axles.

Computer simulations are also performed to study the directional dynamics of a tank vehicle during a delivery route when one of the compartment is emptied by a specific quantity, for example, 6000 ℓ. Removal of 6000 ℓ from a mid-compartment leads to a completely empty compartment. Figure 5.26 presents a comparison of peak roll angle and lateral acceleration response of a four-compartmented five-axle vehicle, subjected to 1 degree steady steer at 50 km/h speed, when 6000 ℓ of the cargo is removed from one of its compartments. The figure clearly illustrates that a tank vehicle with partially filled end compartments yields slightly larger peak response due to motion of the free surface.

5.7.2 TRANSIENT STEER MANOEUVRES

Transient directional response characteristics of five- and six-axle tractor-semitrailer vehicles with one empty compartment are investigated for typical lane change and evasive manoeuvres. Figure 5.27 presents a comparison of roll angle and lateral acceleration response of a four-compartment five-axle tractor-tank-semitrailer vehicle while negotiating a lane change manoeuvre at 90 km/h. The load carried by the tank vehicle is varied by emptying one of the compartments while the other compartments are held fully loaded. A vehicle with an empty mid-compartment exhibits the highest roll angle throughout the manoeuvre, while the roll response is lowest when an end-compartment is emptied first. The corresponding peak lateral acceleration response is observed to be relatively insensitive to location of the empty compartment.

The roll and lateral acceleration response of the tank vehicle with an empty compartment subjected to an evasive manoeuvre is presented in Figure 5.28. The peak roll angle response of tank vehicle with an empty mid-compartment is observed to be approximately 0.5 degree more than that with an empty end compartment. The corresponding lateral acceleration response remains relatively insensitive to location of the empty compartment. The roll angle as well as the lateral acceleration response characteristics of the semitrailer, however, remain almost identical when 6000 ℓ of cargo is removed from one of the compartments, as shown in Figure 5.29.

5.8 Directional Response of Compartmented B-Train Tank Vehicles

B-train vehicles, employed in transportation of fuel oils are often equipped with compartmented tanks of modified-oval cross-section. Directional dynamics of seven- and eight-axle B-trains are investigated for steady and

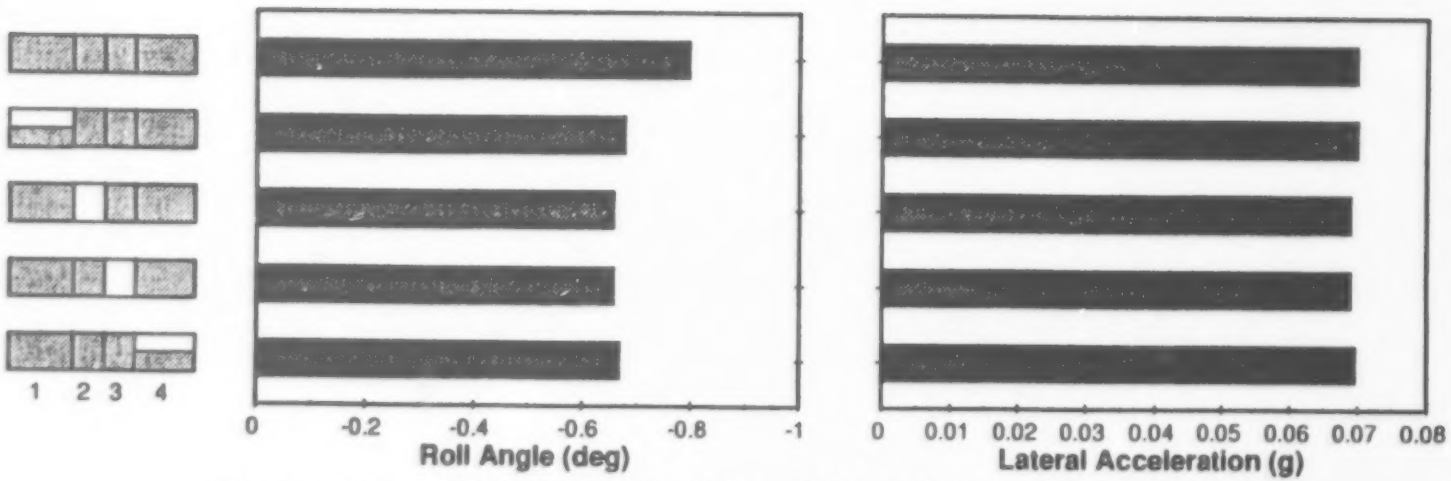
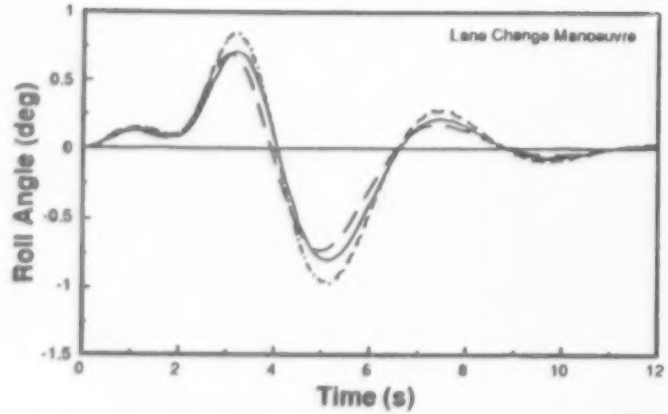
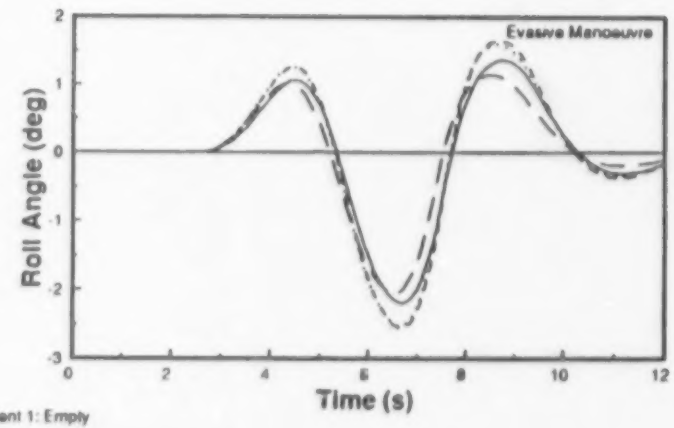


Figure 5.26: Influence of emptying 6000 l from a compartment on vehicle response (Vehicle: 5-axle tractor-semitrailer).





Compartment 1: Empty
Compartment 2: Empty
Compartment 3: Empty
Compartment 4: Empty

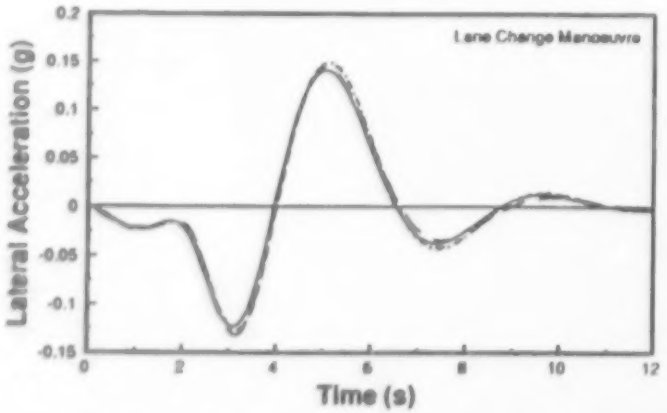


Figure 5.27: Influence of location of an empty compartment on the transient directional response.

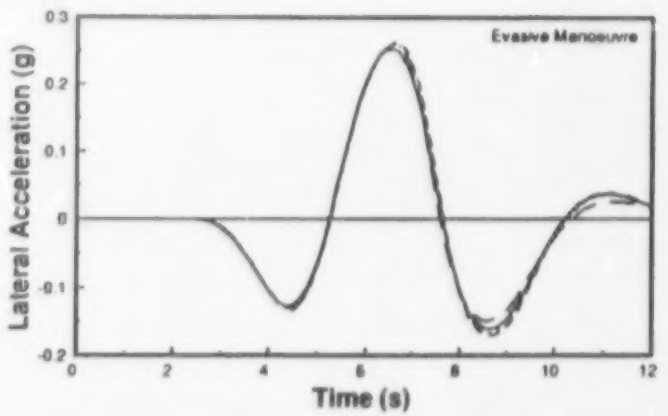


Figure 5.28: Influence of location of an empty compartment on the transient directional response.

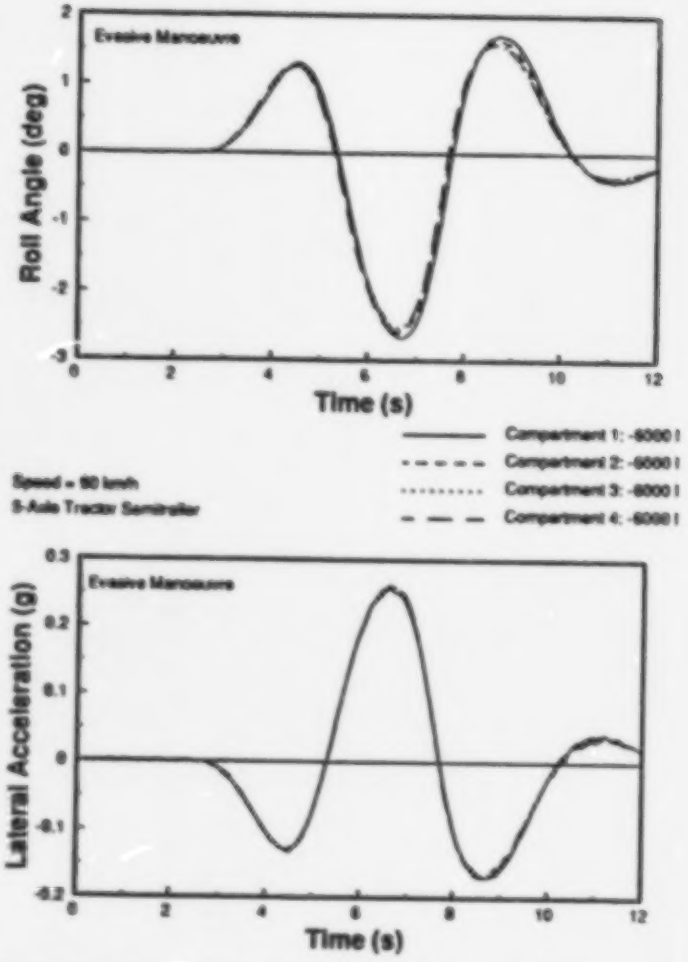


Figure 5.29: Influence of emptying 6000 l from a compartment on the transient directional response.

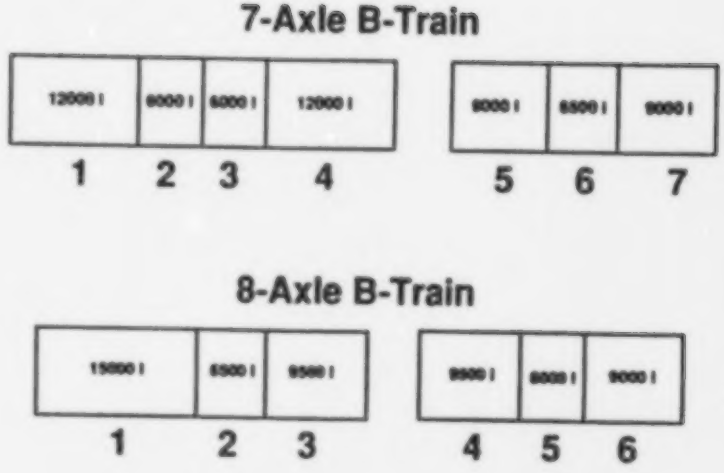


Figure 5.30: Compartment capacities of the B-train tank vehicles.

transient steer manoeuvres. The leading and trailing tank-trailers of the seven-axle B-train are assumed to be designed with four and three compartments, respectively. Each of the tank trailers of the eight-axle B-train is assumed to be designed with three compartments. Capacities of various compartments for the two vehicle configurations are presented in Figure 5.30.

5.8.1 STEADY STEER MANOEUVRES

Figure 5.31 presents a comparison of peak roll angle and lateral acceleration response of the rearmost trailer of a 7-axle B-train tank vehicle subjected to 1 degree steady steer at a speed of 50 km/h. The fully loaded vehicle exhibits highest roll angle response due to high value of overall c.g. height. The tank vehicle with either empty rearmost compartment of leading trailer (#4) or leading compartment of rear trailer (#5) yields the lowest values of peak roll angle and lateral acceleration response. The tank vehicle with one of the smaller size mid-compartment empty (#2, #3, or #6) yields highest value of roll angle. The peak values of roll angle and lateral acceleration response of an eight-axle B-train with one empty compartment is presented in Figure 5.32. The figure clearly illustrates that a tank vehicle with compartment #4 empty (leading compartment of rear trailer) exhibits the lowest value of peak roll angle for the rear trailer, while emptying compartment #1 (leading compartment of lead trailer) yields the highest value of peak lateral acceleration.

5.8.2 TRANSIENT STEER MANOEUVRES

Directional response characteristics of B-train tank vehicles subjected to transient lane change and evasive manoeuvres, are investigated when one of the compartments is completely emptied. Figure 5.33 presents the roll angle and lateral acceleration response of a 7-axle B-train during a lane change manoeuvre, when one of the compartment is completely empty. Emptying compartment #5 yields the lowest roll angle response, while emptying compartment #1 exhibits the highest roll angle response during the manoeuvre. The lateral acceleration response of the compartmented tank vehicle is relatively insensitive to location of the empty compartment.

Figure 5.34 presents the transient roll angle and lateral acceleration response of the 7-axle B-train during an evasive manoeuvre at a speed of 90 km/h. Emptying compartment #5 yields the lowest roll angle response, as in the case of a lane change manoeuvre. Emptying the rearmost compartment (#7), however, yields highest roll angle response. The difference in roll response is approximately 1.2 degrees.

The roll angle and lateral acceleration response characteristics of the 8-axle B-train, subjected to an evasive manoeuvre at 90 km/h are illustrated in Figure 5.35. The tank vehicle combination with empty rearmost compartment (#6) yields the highest values of peak roll angle and lateral acceleration response. Emptying the rearmost compartment of the leading trailer (#3) yields the lowest values of peak roll angle and lateral acceleration during the second lane change and correction phase of the manoeuvre.

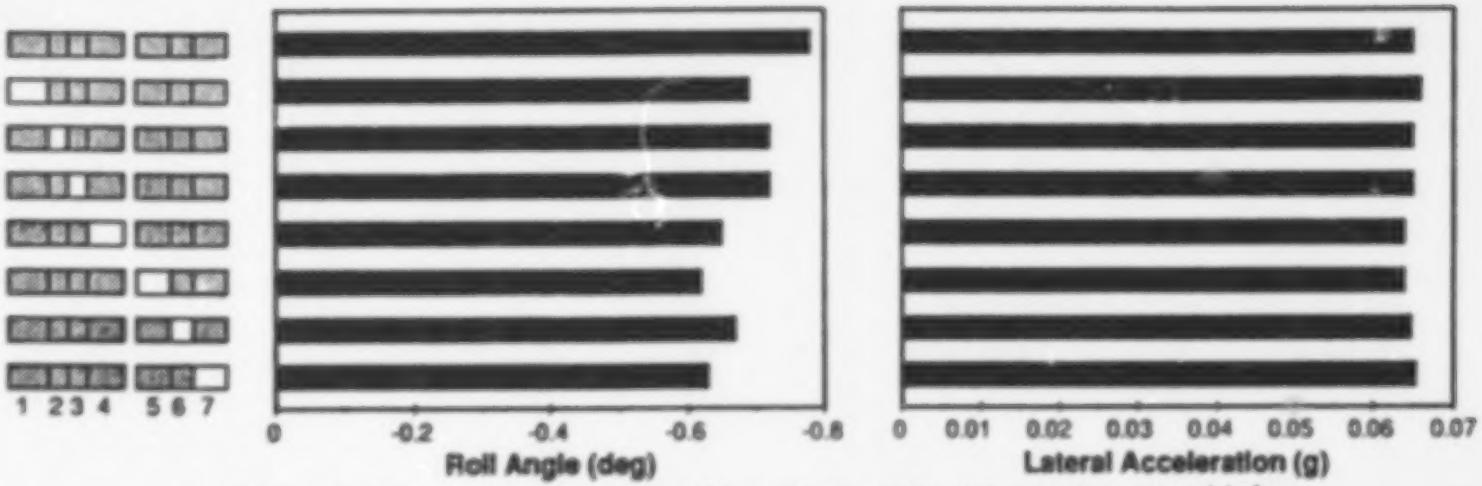


Figure 5.31: Influence of location of an empty compartment on vehicle response (Vehicle: 7-axle B-Train)

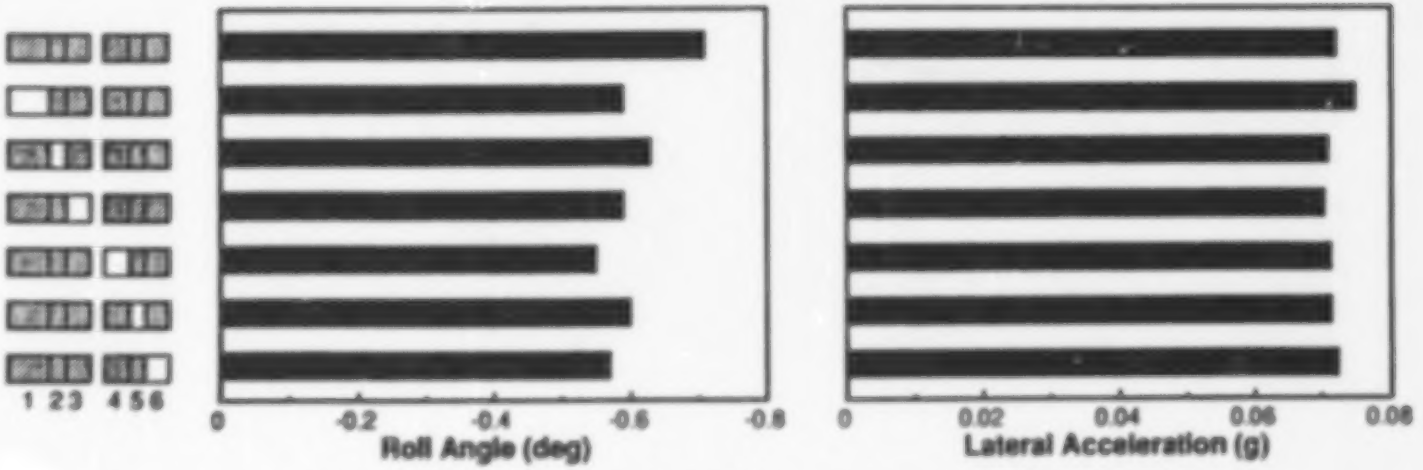


Figure 5.32: Influence of location of an empty compartment on vehicle response (Vehicle: 6-axle B-Train).

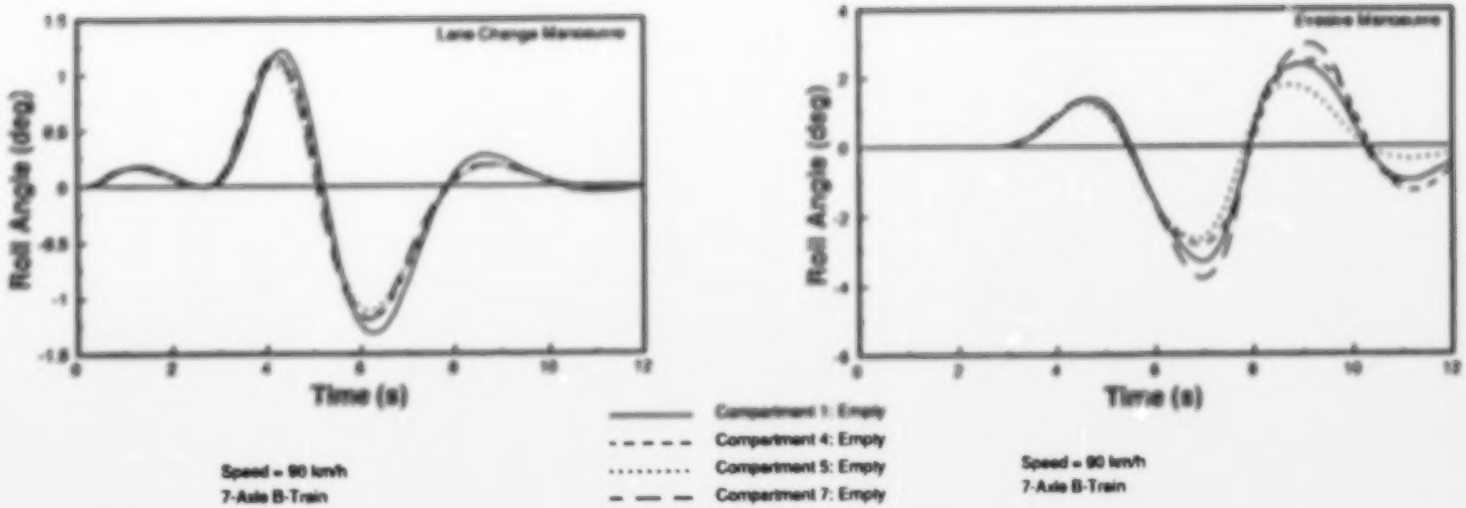
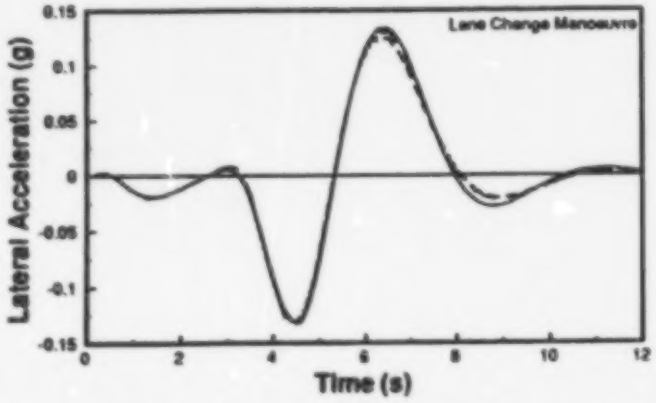
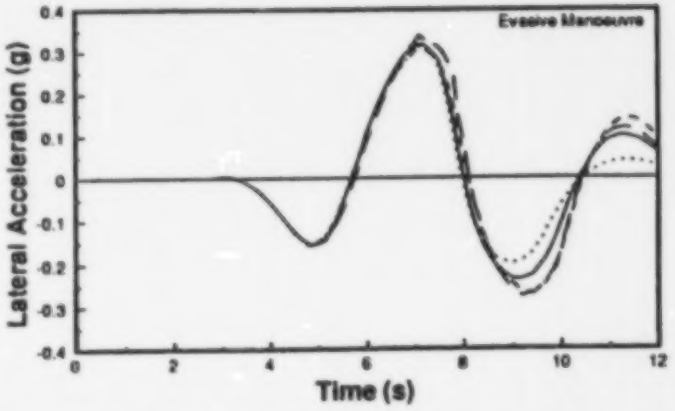


Figure 5.33: Influence of location of an empty compartment on the transient directional response.

Figure 5.34: Influence of location of an empty compartment on the transient directional response.





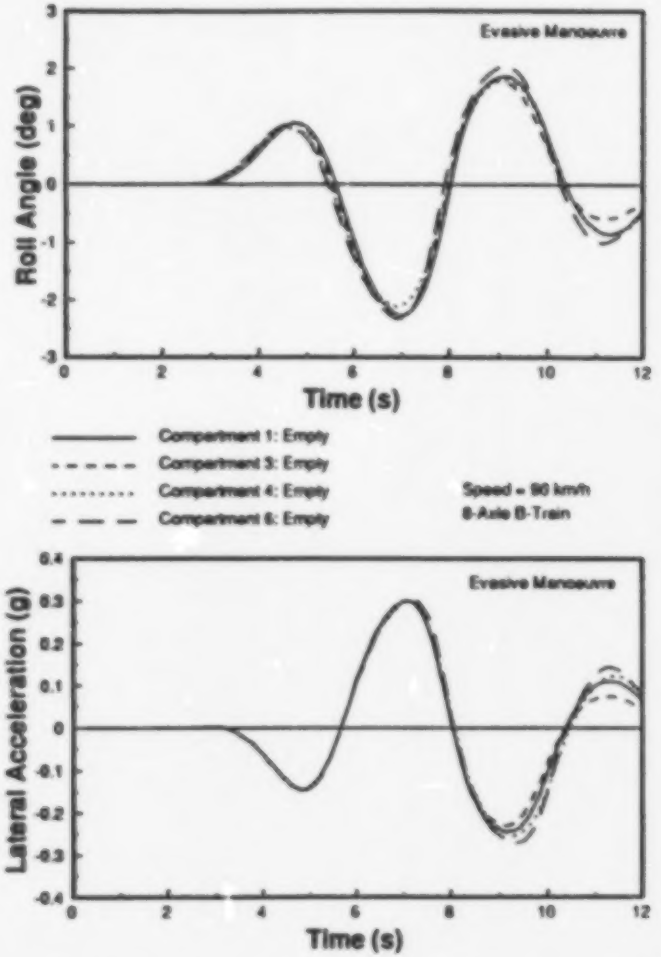


Figure 5.35: Influence of location of an empty compartment on the transient directional response.

6. DYNAMIC FLUID SLOSH MODEL AND DIRECTIONAL DYNAMICS OF TANK VEHICLES

The directional dynamic model of the tank vehicle presented in section 5, incorporates a steady-state fluid slosh model, where the slosh forces and moments are estimated assuming inviscid fluid motion and negligible fluid-vehicle interactions. The dynamic slosh behavicur was neglected by assuming the steer frequency to be considerably lower than the fundamental slosh frequency.

Research investigations on the dynamics of liquid tank vehicles have indicated that directional stability of partially filled tank vehicles is strongly related to the dynamic slosh loads and fluid-vehicle interactions [10]. It is further speculated that the directional dynamics of tank vehicles are also influenced by the fundamental slosh frequency [20]. Although the tank vehicle models incorporating steady-state fluid slosh model do provide the directional behaviour of the vehicle under steady-state assumptions, a study of transient slosh loads is undertaken to investigate the significance of slosh frequencies and their influence on the directional dynamics.

The magnitude and fundamental frequency of fluid slosh is dependent upon tank geometry and fill level. Budiansky [28] developed a relationship between the fill level and fundamental slosh frequency of fluid within a tank using linear fluid theory. Figure 6.1 illustrates the variations in frequencies associated with first and second modes of slosh for various fill levels. The normalized slosh frequency, K, presented in Figure 6.1, is related to the slosh frequency, ω_n, in the following manner:

$$\omega_n = K \sqrt{g / R} \qquad (6.1)$$

where g is acceleration due to gravity and R is tank radius. The figure reveals that the fundamental slosh frequency increases slowly and monotonically with fill level, for fill levels below 60%. The slosh frequency, however, increases rapidly for higher fill levels. The fundamental slosh frequency of fluid within a 2.03 m (80 in) diameter cylindrical tank varies in the range 0.52 - 0.60 Hz for fill levels ranging from 20% to 60%. Although steer frequency corresponding to a rapid lane change or an obstacle avoidance manoeuvre lies near 0.3 Hz, the directional dynamics of tank vehicles with extremely low fill levels subjected to transient manoeuvre at high speeds may be influenced significantly by the fluid slosh.

6.1 Development of a Vehicle Dynamics Model with Dynamics of Fluid Slosh

An articulated tank vehicle equipped with a cleanbore cylindrical tank cross-section is modeled in order to simulate the influence of dynamic liquid slosh forces and moments on its directional response. A 2-dimensional, dynamic liquid slosh model of a partially filled circular cross-section tank is integrated to the yaw and roll model of the tank vehicle, assuming constant vehicle speed. The computer model thus developed is capable of simulating any vehicle combination with a maximum of 4 units and 11 axles. The computer

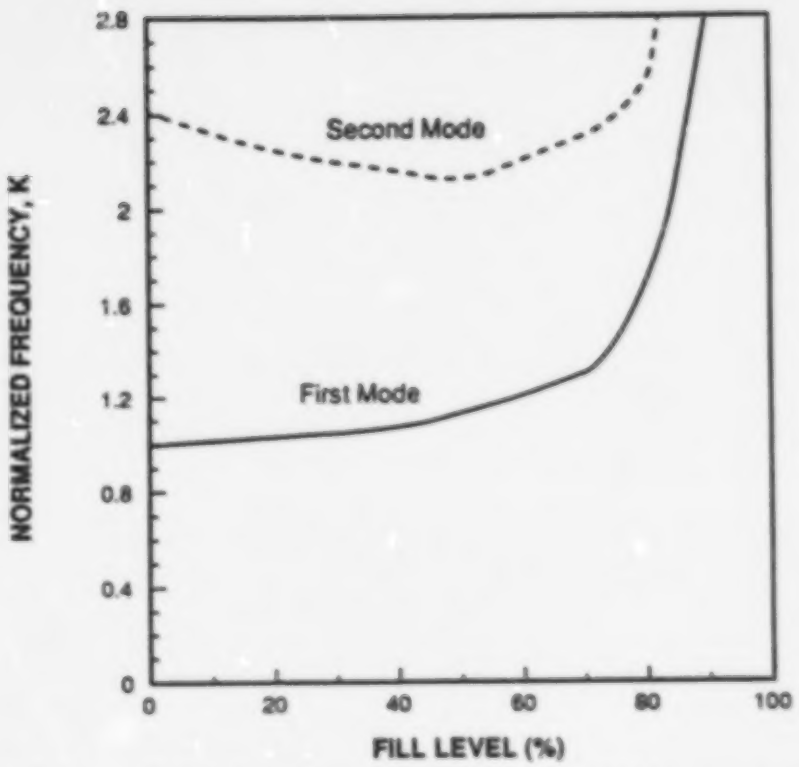


Figure 6.1: Natural frequency of liquid within a partially filled cylindrical tank.

model, however, is extremely demanding on the computing resources due to complex fluid dynamics code. A 5-axle tractor-tank-semitrailer, equipped with a cleanbore cylindrical tank is selected for this complex vehicle-fluid slosh model development.

6.1.1 DEVELOPMENT OF A DYNAMIC FLUID SLOSH MODEL

The Navier-Stokes equations describing fluid motion within the tank are solved in conjunction with boundary conditions and equations of the free surface using finite difference code [27]. Since the non-linear differential equations of fluid motion are solved in a non-dimensional region, the results obtained are true for all geometrically similar class of problems for which the fluid flow numbers, such as the Strouhal, Froude, Euler and Reynold's numbers remain identical. The fluid forces are computed by integrating the pressure distribution along the wetted wall, separately in the horizontal and vertical directions. The overturning moment about the tank base is computed from the force components and their location.

When a partially filled liquid tank is accelerated, the velocities, pressure, fluid height and fluid forces undergo an oscillatory motion with certain frequency dictated by the tank geometry, fluid properties and nature of excitation. The solution of the fluid equations provides instantaneous slosh forces and moments which are then integrated to the vehicle dynamics model in order to compute directional response of the tank vehicle.

6.1.2 ANALYTICAL MODEL OF THE TANK VEHICLE

A five-axle articulated tank vehicle is modeled to compute its dynamic response to liquid slosh forces and moments. The set of differential equations of motion of the sprung mass, derived in Section 5, are modified to account for the slosh forces and moments. The final set of equations describing the directional dynamics of tank vehicles are expressed as follows:

Lateral Force Equations

$$m_f a_f \vec{j}_{sf} = \text{(Lateral components of constraint and suspension forces)} + (m_f + m_{\ell f}) g \theta_{sf} + F_{yf} \qquad (6.2)$$

Vertical Force Equations

$$m_f a_f \vec{k}_{sf} = \text{(Vertical components of constraint and suspension forces)} + m_f g + F_{zf} \qquad (6.3)$$

Roll Moment Equations

$$(I_{xf} + I_{x\ell f})\,\dot{p}_f - (I_{yf} + I_{y\ell f} - I_{zf} - I_{z\ell f})\, q_f r_f = \text{(Roll moments due to constraint and suspension forces)} + OM_f + m_{\ell f} g\,(\theta_{sf} Z_{\ell f} + Y_{\ell f}) \qquad (6.4)$$

Pitch Moment Equations

$$(I_{yf} + I_{y\ell f})\,\dot{q}_f - (I_{zf} + I_{z\ell f} - I_{xf} - I_{x\ell f})\,p_f r_f =$$

(Pitch moments due to constraint and suspension forces)

$$- F_{zf}\,X_{\ell f} - m_{\ell f}\,g\,(X_{\ell f} + \alpha_{sf}\,Z_{\ell f}) \qquad (6.5)$$

Yaw Moment Equations

$$(I_{zf} + \sum_{i=N_1}^{N_2} I_{zui} + I_{z\ell f})\,\dot{r}_f - (I_{xf} + I_{x\ell f} - I_{yf} - I_{y\ell f})\,p_f q_f =$$

(Yaw moments due to constraint and suspension forces) - $F_{yf}\,X_{\ell f}$ (6.6)

where

$$N_1 = \begin{cases} 1 \\ \\ 4 \end{cases} ; \quad N_2 = \begin{cases} 3 \\ \\ 5 \end{cases} ; \text{ for } f = \begin{cases} 1 \\ \\ 2 \end{cases} \qquad (6.7)$$

F_{yf} and F_{zf} are horizontal and vertical slosh forces respectively, and OM_f is the overturning slosh moment about the c.g. of the trailer's sprung weight. The slosh forces and the moments, however, vanish for the tractor unit (f = 1) due to absence of the liquid cargo.

6.2 Method of Solution

The solution procedure is initiated by solving the differential equations of motion describing the yaw and roll dynamics of the vehicle through numerical integration. Equations of motion are initially solved for a small increment in time to compute roll angle and lateral acceleration of the tank for a given steer input. The lateral and vertical accelerations of the tank along the sprung mass coordinates are transformed to non-dimensional accelerations along the tank axes. The accelerations are then incorporated as sources of excitation to the dynamic fluid slosh model to compute the slosh forces and moments during that time increment. The computed slosh forces and moments are then incorporated back into the vehicle model in order to compute the lateral and vertical sprung mass accelerations of the tank vehicle during the next time increment. The free surface of liquid in the slosh model is kept "frozen" while the vehicle response calculations are performed. The sequential interactive procedure is shown in Figure 6.2.

6.3 Directional Response of the Tank Vehicle

The directional response of a five-axle tractor-semitrailer liquid tank

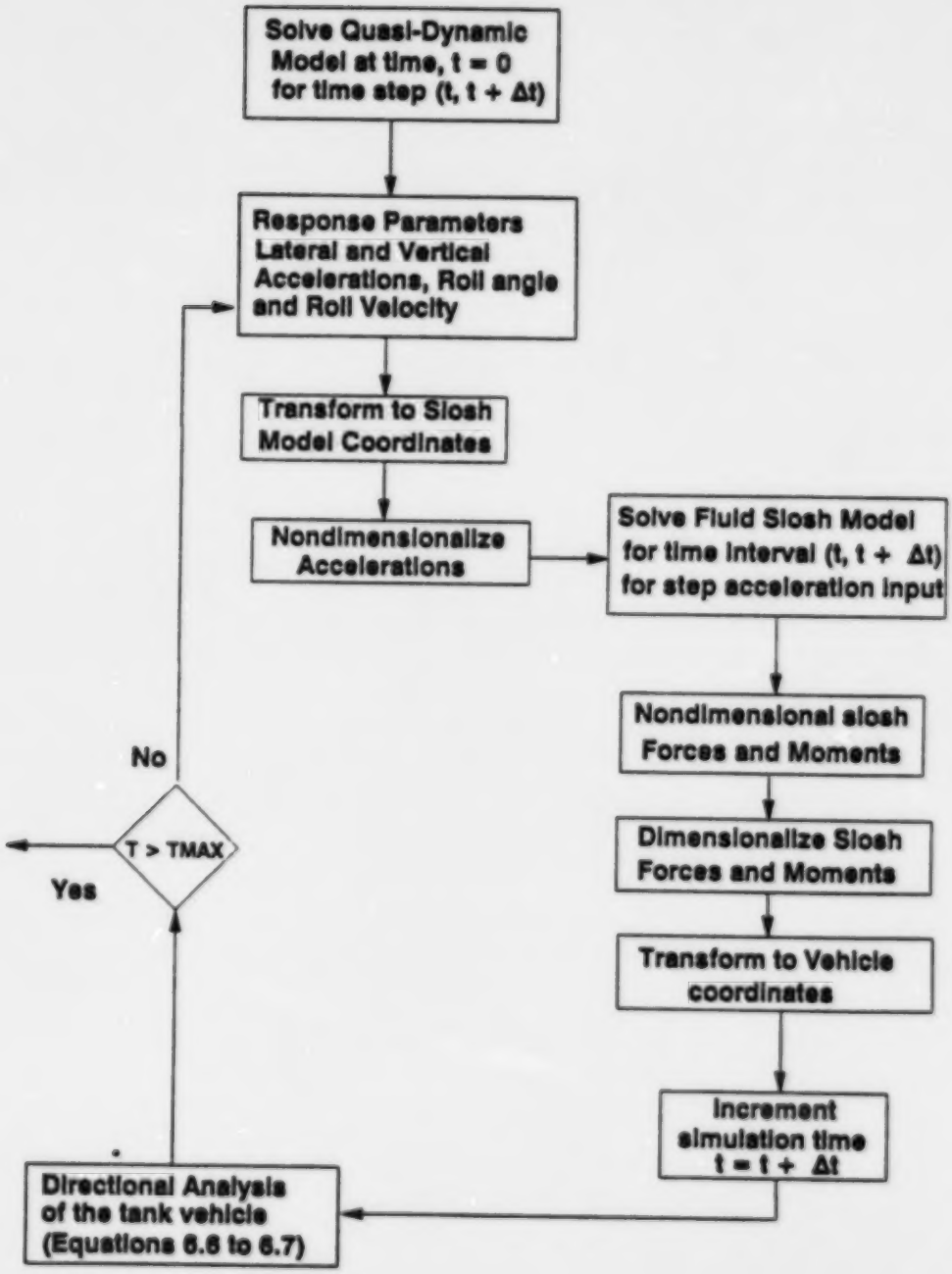

Solve Quasi-Dynamic Model at time, t = 0 for time step (t, t + Δt)
Response Parameters Lateral and Vertical Accelerations, Roll angle and Roll Velocity
Transform to Slosh Model Coordinates
Nondimensionalize Accelerations
Solve Fluid Slosh Model for time interval (t, t + Δt) for step acceleration input
Nondimensional slosh Forces and Moments
Dimensionalize Slosh Forces and Moments
Transform to Vehicle coordinates
Increment simulation time t = t + Δt
Directional Analysis of the tank vehicle (Equations 6.6 to 6.7)
T > TMAX
No
Yes

Figure 6.2: Flow diagram of the computational procedure

vehicle equipped with a cleanbore cylindrical tank is investigated for typical highway manoeuvres using the procedure outlined in the previous section. The simulation results are then compared to those obtained using the steady-state fluid slosh model derived in Section 5. The response simulations are carried out for both steady and transient steer inputs under constant axle loading conditions.

6.3.1 CONSTANT STEER MANOEUVRE

The directional response characteristics of a tank vehicle equipped with a cleanbore cylindrical tank is investigated for constant steer input. The dynamic slosh forces and moments arising within the partially filled tank are computed using dynamic fluid slosh model. The cylindrical tank is partially filled with fuel oil of weight density 0.0068 N/cm^3 (0.025 lb/in^3). The fill levels within the tank are altered by changing the weight density of the fluid such that the payload remains constant.

Computer simulations are carried out to determine the directional response of a tank vehicle subjected to 2 degrees constant steer input at a constant vehicle speed of 60 km/h. The roll response of a 70%-filled tank vehicle subjected to liquid slosh forces is compared to that of the tank vehicle employing the quasi-dynamic model and is shown in Figure 6.3. The roll response of the quasi-dynamic model reaches a steady state value of 1.71 degrees. The roll response of the sprung mass incorporating dynamic fluid slosh model, however, exhibits damped oscillation due to the oscillations of the fluid within the partially filled tank. The fluid oscillates at its fundamental mode of vibration around a mean roll angle of 1.52 degrees. The frequency of oscillation is approximately 0.67 Hz which is quite close to the value derived using the linear approximation theory [28]. The amplitude of roll oscillation decreases gradually with the simulation time. Figure 6.3 also reveals that there is a marginal overestimation of the roll response of the tank vehicle when the quasi-dynamic model is utilized.

The lateral acceleration response of a tank vehicle incorporating the dynamic fluid slosh model is compared to the quasi-dynamic model and is shown in Figure 6.4. The steady-state lateral acceleration response of the vehicle employing quasi-dynamic fluid model approaches 0.184 g, while the response of the dynamic fluid slosh model oscillates around 0.175 g. Figure 6.5 presents a comparison of the roll rate responses for dynamic and quasi-dynamic fluid slosh models. The roll rate response of the vehicle employing a quasi-dynamic model quickly approaches a steady-state value of zero. In the case of the dynamic slosh model the roll rate response oscillates around zero mean at the fundamental slosh frequency and its amplitude decays with time.

Fill level within the tank is altered by changing the weight density of liquid such that the payload is held constant. The roll response of a 50%-filled tank vehicle subjected to a constant steer manoeuvre (2 degrees), at 60 km/h, is presented in Figure 6.6. A comparison of Figures 6.3 and 6.6 reveals that frequency of oscillation decreases when the fill level is reduced while the amplitude of oscillations grows with low fill level. The frequency of oscillation is approximately 0.59 Hz. The roll response of the vehicle employing the quasi-dynamic fluid model reaches a steady state value of 1.71 degrees, similar to that for a 70%-filled tank vehicle shown in Figure 6.3.

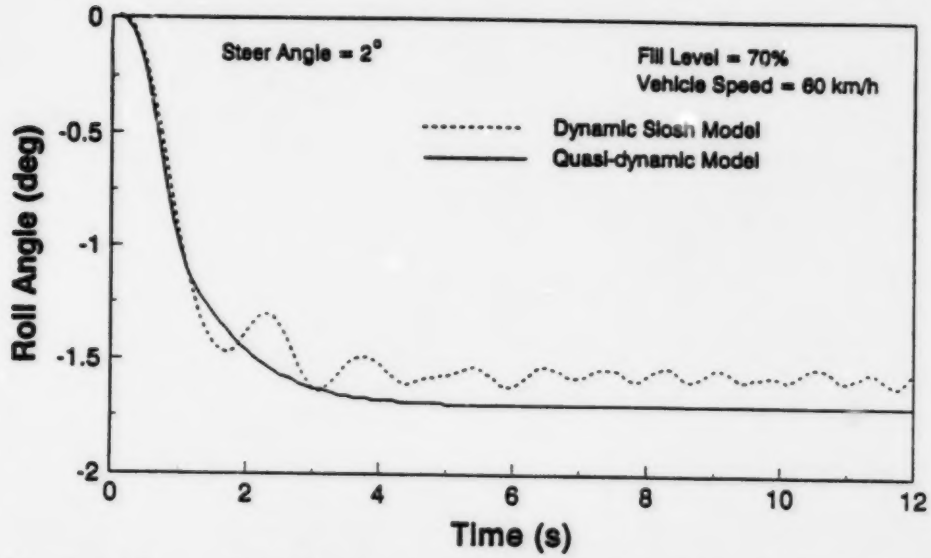


Figure 6.3: Comparison of roll angle response of dynamic slosh and quasi-dynamic tank vehicle models.

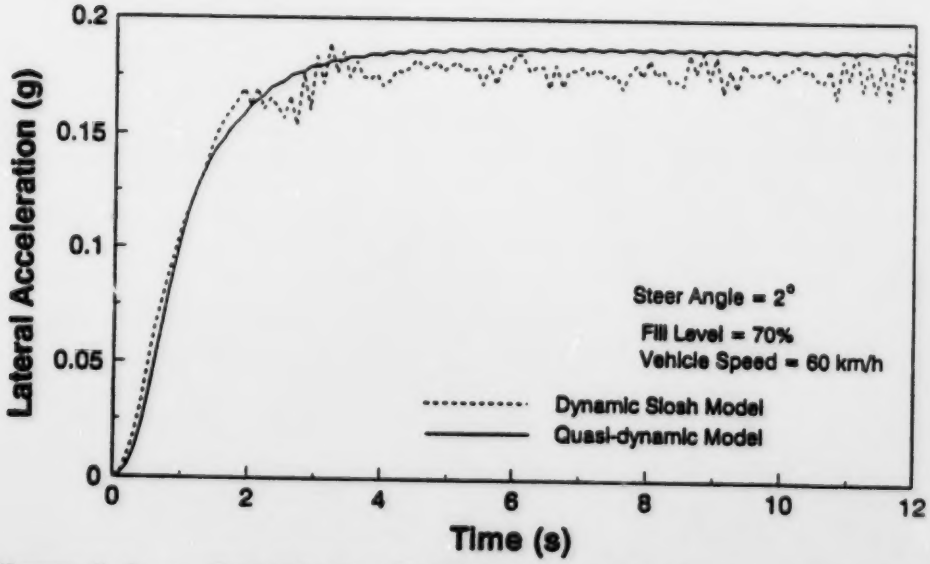


Figure 6.4: Comparison of lateral acceleration response of dynamic slosh and quasi-dynamic tank vehicle models.

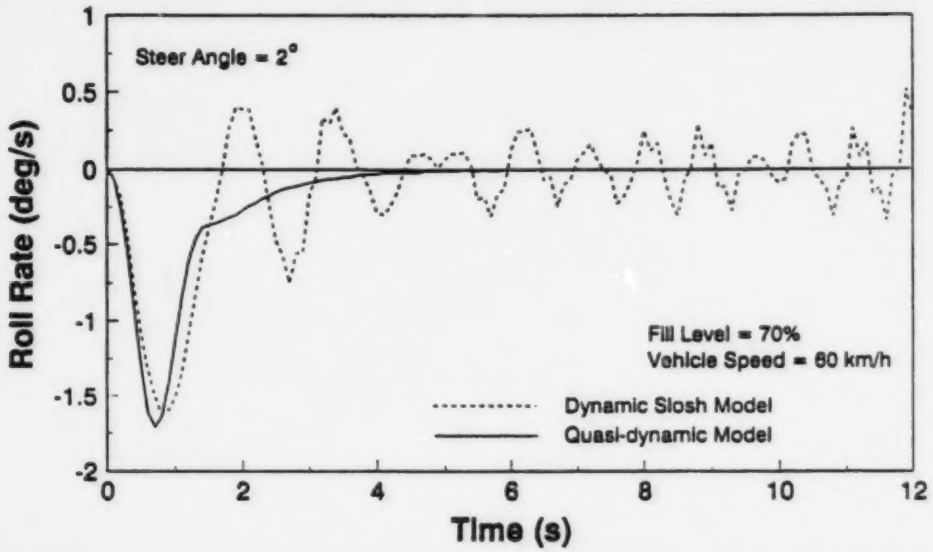


Figure 6.5: Comparison of roll rate response of dynamic slosh and quasi-dynamic tank vehicle models.

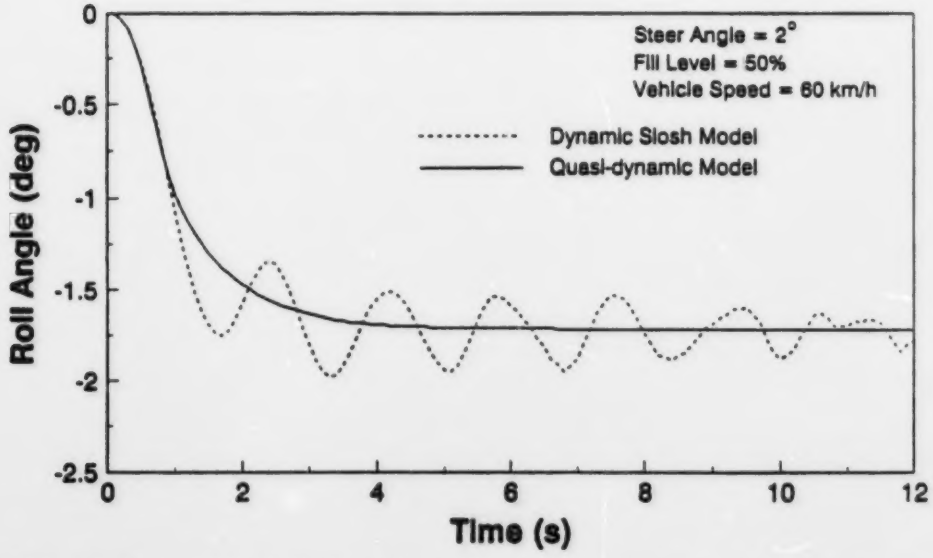


Figure 6.6: Comparison of roll angle response of dynamic slosh and quasi-dynamic tank vehicle models.

With the total payload held constant, the decrease in fill level yields lower overall centre of mass height. The magnitude of liquid load shift, however, increases due to increased sloshing. Thus, the steady-state roll response characteristics for both 50% and 70%-filled tank vehicles are quite similar. The dynamic roll response of the vehicle employing the fluid slosh model reveals oscillations about a mean value of 1.72 degrees. The amplitude of roll oscillations decreases gradually after the steer angle approaches a constant value.

6.3.2 TRANSIENT STEER MANOEUVRES

The directional response characteristics of a 50%-filled tank vehicle are investigated for typical lane change and evasive manoeuvres at highway speeds using a dynamic fluid slosh model. The directional response characteristics are compared to those computed using a quasi-dynamic model. Figure 6.7 presents a comparison of the roll response of a 50%-filled tank vehicle during a lane change manoeuvre at a vehicle speed of 90 km/h. It reveals that the quasi-dynamic model can predict the vehicle roll response almost as accurately as the dynamic fluid slosh model. The dynamics of fluid slosh within the partially filled tank, however, increases the peak roll response of the trailer, as shown in Figure 6.7. The fluid slosh also results in an oscillatory roll response around a zero value after completion of the manoeuvre. In case of the quasi-dynamic model the roll angle response, however, approaches zero at the end of a similar manoeuvre. The steer frequency for the lane change manoeuvre is around 0.25 Hz which is well below the fundamental slosh frequency of a 50%-filled tank.

The corresponding lateral acceleration response characteristics of tank vehicles employing quasi-dynamic and dynamic slosh models are presented in Figure 6.8. The lateral acceleration response evaluated using the quasi-dynamic model is quite close to that evaluated from the dynamic slosh model. The peak acceleration response of the vehicle employing the dynamic slosh model, however, is slightly higher than that employing the quasi-dynamic model during the correction phase of the manoeuvre. Figure 6.9 presents the corresponding roll rate response of the tank vehicle during lane change manoeuvre. The fluctuations in roll rate about zero mean arise from the dynamics of fluid oscillation within the tank. The high frequency oscillations in the response for dynamic slosh model may be attributed to the error involved in the sequential procedure employed to compute the vehicle response.

The influence of fill level on the dynamic response of tank vehicle during a lane change manoeuvre is presented in Figure 6.10. The 30%-filled tank vehicle experiences the highest roll angle while the 70%-filled tank experiences the least roll angle. The roll response of the tank vehicle experiences first mode oscillations after the manoeuvre is completed.

Figure 6.11 presents the roll angle response of a 50%-filled tank vehicle negotiating a double-lane change (evasive) manoeuvre at a vehicle speed of 70 km/h. The roll angle response of tank vehicle incorporating the dynamic slosh model is very close to that of the vehicle employing the quasi-dynamic model during the first lane change of the manoeuvre. The peak roll angles of the vehicles during the second lane change of the manoeuvre reach 2 degrees and

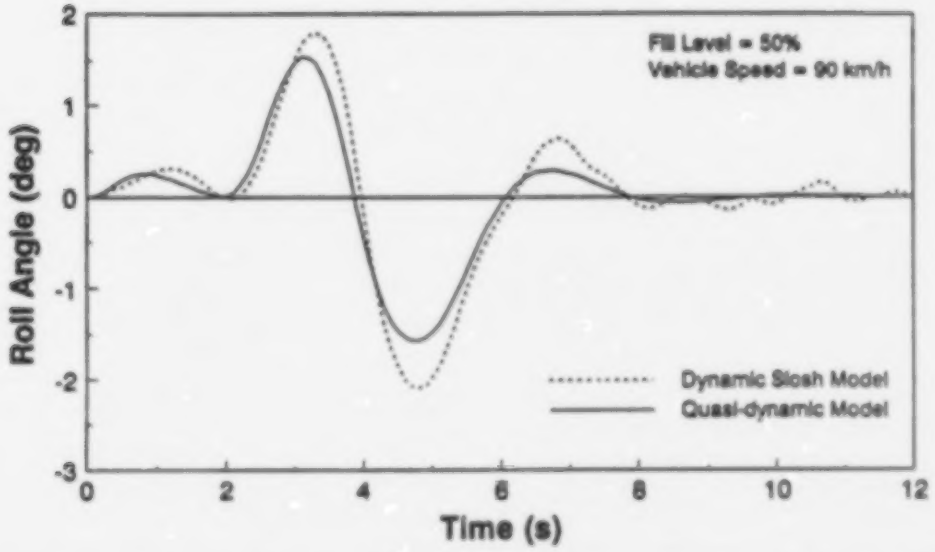


Figure 6.7: Comparison of roll angle response of dynamic slosh and quasi-dynamic vehicle models for a lane change manoeuvre.

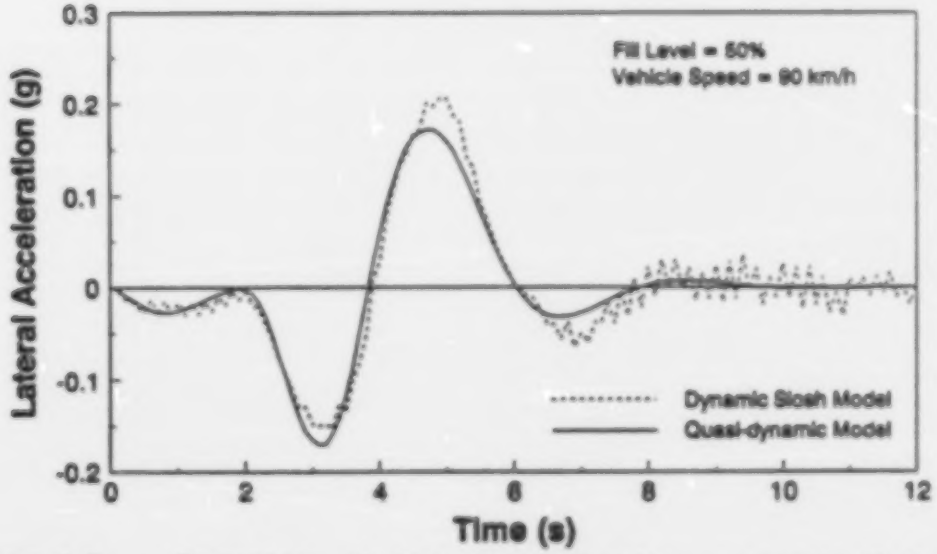


Figure 6.8: Comparison of lateral acceleration response of dynamic slosh and quasi-dynamic vehicle models for a lane change manoeuvre.

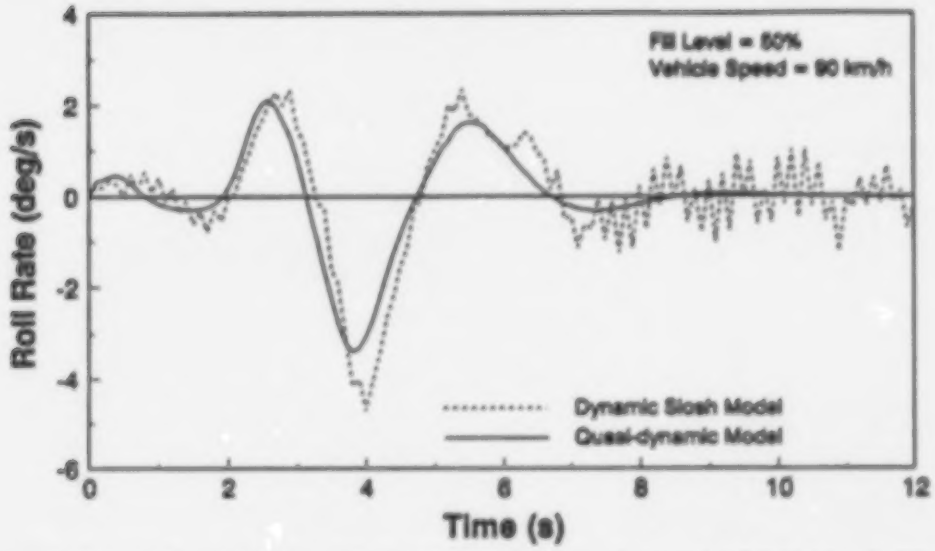


Figure 6.9: Comparison of roll rate response of dynamic slosh and quasi-dynamic vehicle models for a lane change manoeuvre.

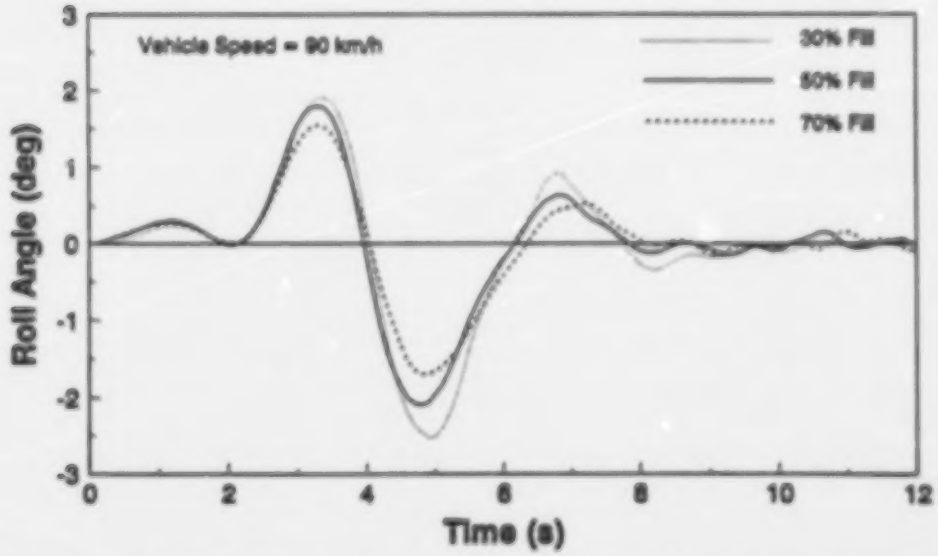


Figure 6.10: Influence of fill level on the roll angle response of dynamic slosh vehicle model for a lane change manoeuvre.

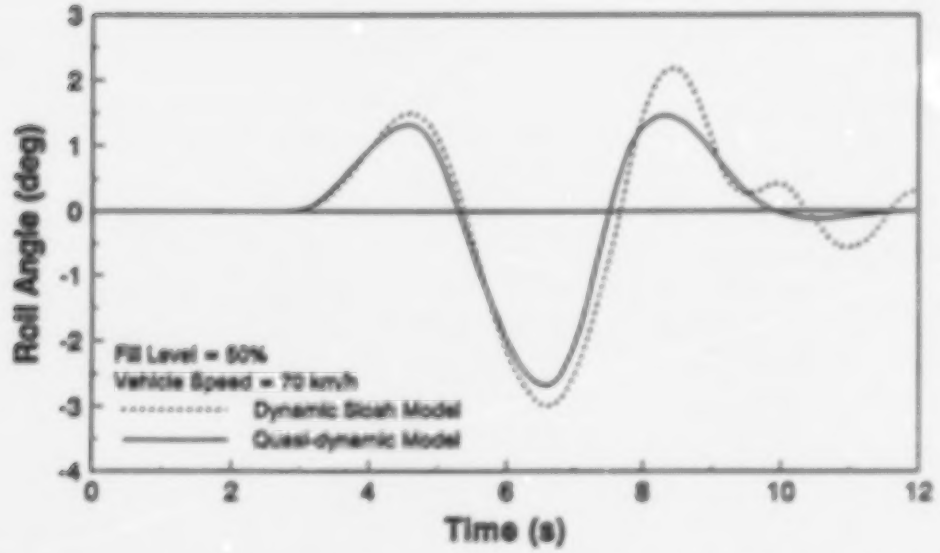


Figure 6.11: Comparison of roll angle response of dynamic slosh and quasi-dynamic vehicle models for an evasive manoeuvre.

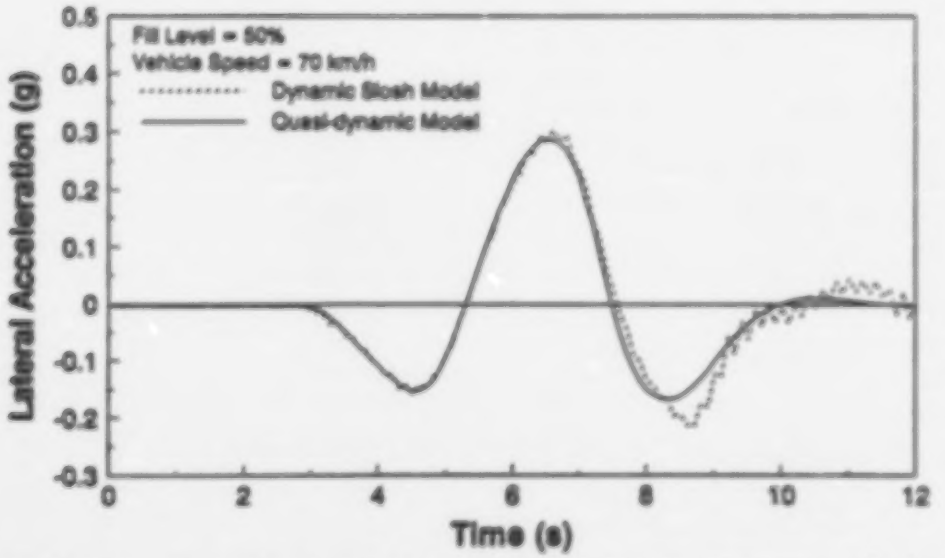


Figure 6.12: Comparison of lateral acceleration response of dynamic slosh and quasi-dynamic vehicle models for an evasive manoeuvre.

1.4 degrees, respectively for dynamic and quasi-dynamic models. This deviation can be attributed to the difference in the steer frequencies for the first and second lane change. The frequencies of the first and second lane change manoeuvres are approximately 0.24 Hz and 0.33 Hz respectively. Hence, the roll angle response of the tank vehicle increases during the second lane change. Figure 6.11 also indicates that the roll angle of the tank vehicle oscillates about the zero value due to the continued fluid motion within the tank even after the manoeuvre is completed. The lateral acceleration response of the vehicle employing the dynamic slosh model indicates response behaviour identical to the the vehicle employing the quasi-dynamic model, as shown in Figure 6.12. The response plots seem to indicate that a quasi-dynamic fluid model can predict the vehicle response characteristics almost as accurately as the fluid slosh model during various highway manoeuvres.

In view of the extensive computing requirements and complexities associated with tank vehicle model employing comprehensive dynamic fluid slosh model, it is quite appropriate to estimate the directional stability limits of tank vehicles with a steady state fluid model.

7. FIELD TESTING AND VALIDATION OF DIRECTIONAL DYNAMIC MODELS OF TANK VEHICLES

Directional dynamic models, in general, need to be validated either through laboratory or field testing. The tank vehicle models, when validated, can provide confidence in the computer code developed to investigate their directional behaviour. A comprehensive field test program was carried out in collaboration with *Ministry of Transportation Ontario* (MTO). The field data acquired for various directional manoeuvres is analyzed to investigate the directional response characteristics of the test vehicle. The computer simulation results are then compared to those established via field tests to estimate the validity of the analytical model.

7.1 Description of the Test Vehicle

In view of the extensive costs and complexities associated with performing tests on a real size tank vehicle combination, the field tests were conducted on a two-axle tractor mounted with a translucent cylindrical tank. The test vehicle is a 1976 Ford L9000 Model K907 2-axle tractor, equipped with multi-leaf suspension springs and 11R 22.5 Michelin radial tires on both the front and rear axles. The wheelbase of the truck is 4.13 m (162.5 in). The front and rear axles are rated at 53.4 kN (12,000 lb) and 93.45 kN (21,000 lb), respectively. The force-deflection characteristics of the front and rear suspension springs were determined through laboratory testing conducted by the *University of Michigan Transportation Research Institute* (UMTRI). The specifications of the front and rear axles and the force-deflection characteristics of the suspension spring are presented in reference [26].

A translucent cylindrical tank was selected so that the liquid motion within the tank can be seen. The tank is equipped with an inlet port on the top and an outlet manifold at the bottom for loading and unloading. The specifications of the tank are listed in Table 7.1. The tank was filled with water during the field testing, however, a coloring agent was added to facilitate the flow visibility. The tank is mounted on the truck through a mounting assembly which comprises of a main frame, a subframe, and a saddle adapter. The main frame is rigidly fixed to the chassis while the subframe is supported through force transducers on the main frame. A total of three force transducers are mounted vertically between the subframe and the mainframe to measure the dynamic forces and load shift during a manoeuvre. The tank is mounted on the tank saddle which in turn is welded to the saddle adapter and firmly bolted to the subframe. Figure 7.1 presents the tank mounting frame assembly. The complete assembly of the tank and the mounting frame is installed on the tractor such that the geometric centre of the tank lies directly above the centre of the rear axle of the vehicle in the roll plane. Figure 7.2 presents the rear and side views of the tank assembly.

The field tests were conducted for various fill conditions and steering manoeuvres. The liquid loads measured corresponding to various fill conditions are listed in Table 7.2. The corresponding axle loads are listed in Table 7.3. The tests were conducted at the *Ministry of Transportation Ontario Vehicle Test Centre*, Centralia. A long test track was used in order to achieve desired test speeds. All tests were conducted on uniform and dry pavements. The test course revealed a cross slope of approximately 0.3 to 0.5 degrees in one of the test tracks creating a bias roll angle under static

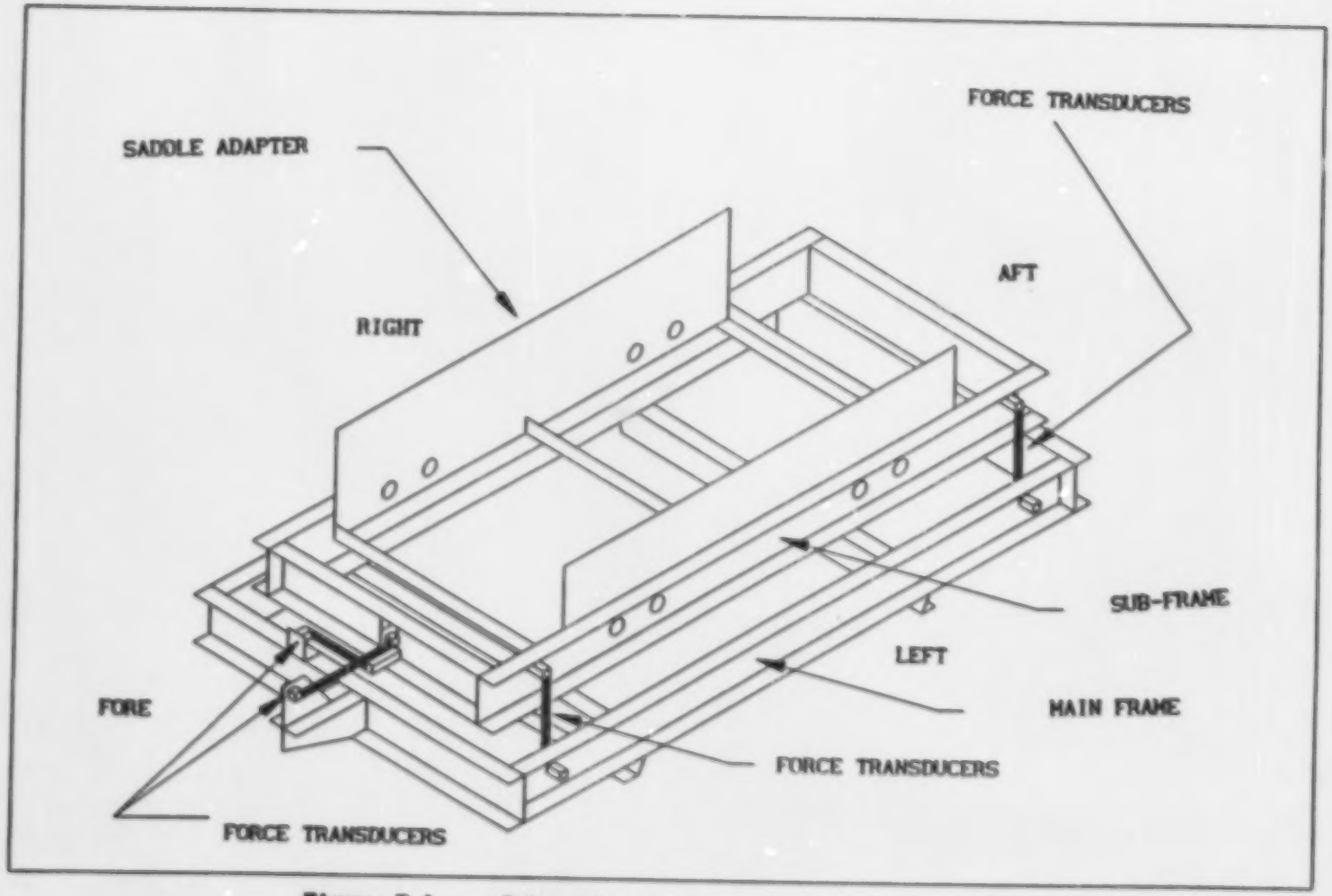
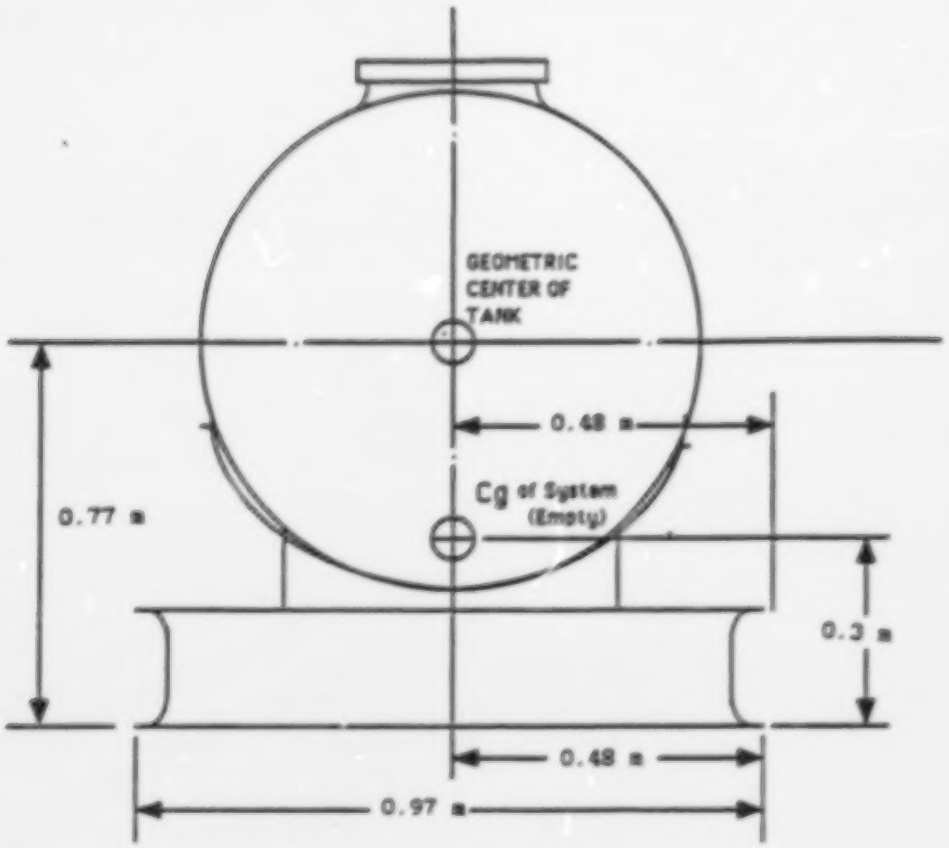


Figure 7.1: Schematic of the mounting frame assembly.



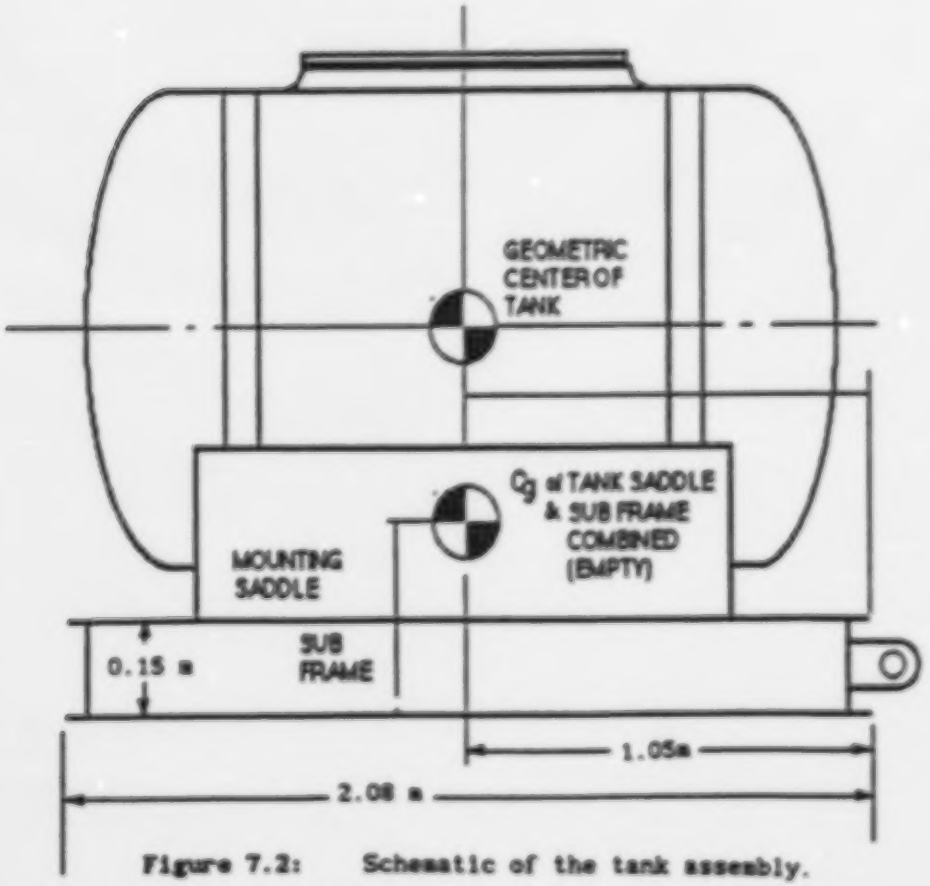


Figure 7.2: Schematic of the tank assembly.

conditions.

TABLE 7.1
SPECIFICATIONS OF THE TEST TANK

Weight	614 N (138 lb)
Volume	1.89 m^3 (500 Gallons)
Diameter	1.22 m (48 in)
Length	1.73 m (68 in)

7.2 Test Manoeuvres

The field tests were conducted for the following test manoeuvres:

- 30 m constant radius turn
- Lane change manoeuvre
- Constant steer
- Straight line braking
- Braking in a turn

Validation of the computer model is presented for the 30m constant radius turn and the lane change manoeuvres.

7.2.1 30 M CONSTANT RADIUS TURN

Commercial vehicles often exhibit roll instabilities during cornering or while negotiating a tight interchange ramp. During this manoeuvre, the lateral acceleration increases gradually as the vehicle negotiates the corner and then remains at a more-or-less steady value (assuming constant speed and turn radius) until the turn is completed. The vehicle exits from the turn tangential to the turn radius after completing a turn of 90 degrees. Such a scenario was simulated in the field with a 30 m turn radius at three different vehicle speeds: 29 km/h; 35 km/h; and 39 km/h. The vehicle speeds were chosen such that the driver was able to attain the specified speed before entering the manoeuvre and maintain it throughout the manoeuvre. The test vehicle approaches the turn radius at the specified speed and negotiates the turning manoeuvre, as shown in Figure 7.3, by tracking the cones with the inner (left) front wheel before exiting from the turn.

TABLE 7.2
LIQUID LOAD AND CORRESPONDING FILL LEVELS

Load (kN)	% Fill	Ht. above Tank Base (m)
0	0	0.0
5.51	30	0.41
7.36	40	0.51
9.25	50	0.59
11.14	60	0.69
13.03	70	0.78
18.63	100	1.22

TABLE 7.3
FILL LEVELS AND CORRESPONDING AXLE LOADS

Liquid Load (kN)	% Fill	Load on the Front Axle (kN)	Load on the Rear Axle (kN)
0	0	35.956	28.658
5.51	30	35.912	34.443
7.36	40	35.912	36.490
9.25	50	35.867	38.315
11.14	60	35.867	40.139
13.03	70	35.867	41.786
18.63	100	35.867	47.386

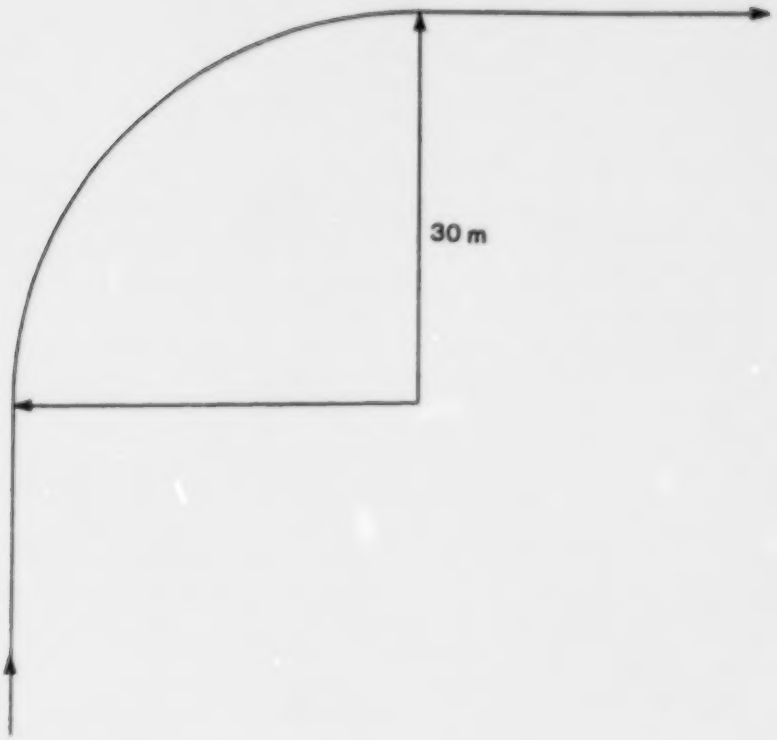


Figure 7.3: Trajectory of a 30 m radius manoeuvre.

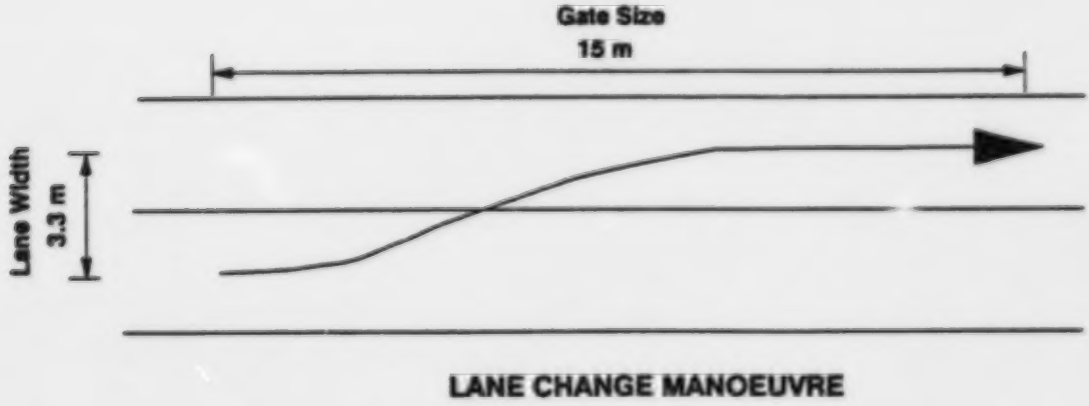


Figure 7.4: Trajectory of 15 m lane change manoeuvre.

7.2.2 LANE CHANGE MANOEUVRES

Multiple articulated vehicle combinations experience high rearward amplification of the roll and lateral acceleration response during a lane change manoeuvre. This can lead to large sway of the rearmost trailer, increased side-slip, lateral accelerations and possible overturning. The influence of liquid motion within the tank-trailers could worsen the directional dynamics of the partially filled tank vehicles. Although the test vehicle under study was a straight truck, the influence of liquid motion within the tank could possibly increase the side-slip on the tractor axles leading to overshoot in the vehicle path and increased roll and lateral acceleration response. In order to examine this tendency, the single lane change manoeuvre was chosen. Three vehicle speeds (35, 39, and 45 km/h) were chosen along with three different gate sizes (15, 18, and 21 m) for the lane change manoeuvre, as shown in Figure 7.4. The driver was instructed to enter the approach lane at its centre at a specified speed and attempt to complete the lane change, to the left, within the distance allowed by the "gate".

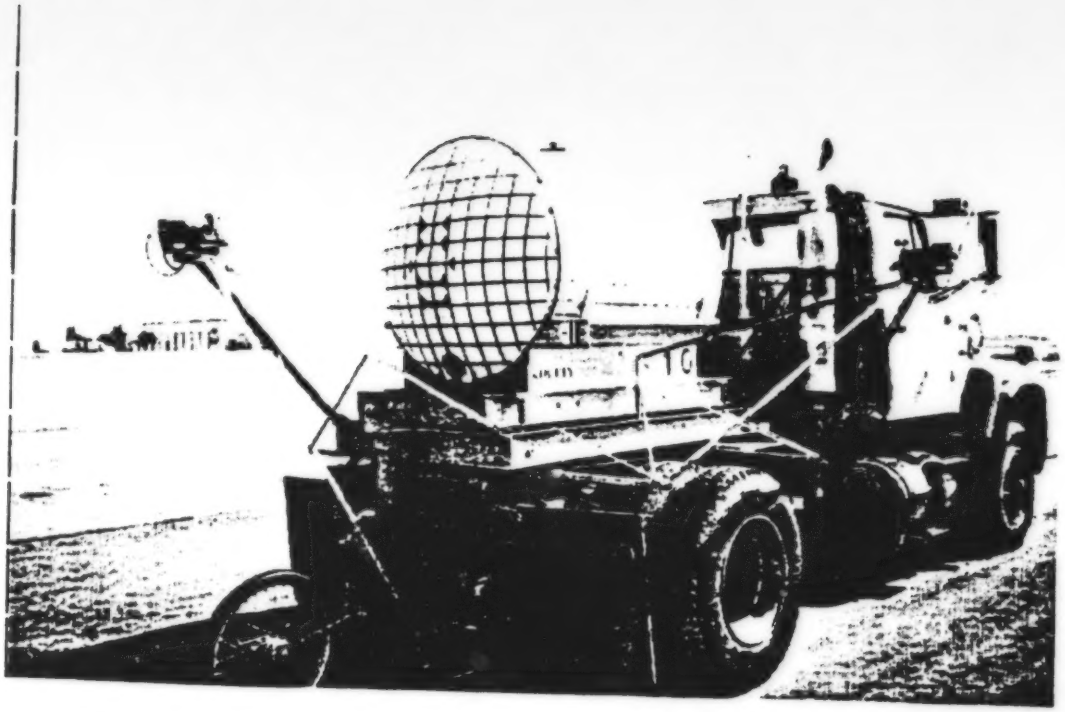
7.3 Instrumentation

The test vehicle was instrumented to measure a wide range of dynamic variables related to liquid slosh and the directional dynamics of the vehicle. The tank was supported on three vertically mounted force transducers: two on the left side and one on the right side. A force transducer was mounted laterally between the sub-frame and the main frame to measure the lateral forces at the tank mounts. A gyro was installed at the tractor's chassis to measure the roll and yaw angles, and the roll and yaw rates of the sprung mass. The lateral acceleration of the vehicle's sprung mass was measured using a piezo-resistive accelerometer. The relative roll angle of unsprung mass with respect to the sprung mass was measured using a potentiometer and the vehicle speed was monitored using a fifth wheel tachometer.

The measured signals were recorded on analog tape using a Metraplex Model 300 FM multiplexing unit capable of recording up to to 42 variables. The recorded data of interest were digitized for post-processing and analyses. The procedure involved in data collection and processing are fully described in the reference [29]. The vehicle was equipped with two video cameras: one at the rear and the other on the side of the vehicle to record the liquid motion within the tank during the test manoeuvres. The acquired raw data was then imported into "Lotus worksheets", and the necessary response plots were obtained. The test vehicle with its instrumentation package is pictured in Figure 7.5.

7.4 Comparison of Simulation and Field Test Results

The test vehicle is modeled to characterize its yaw and roll dynamics using the methodology presented in Section 5. Computer simulations are performed using quasi-dynamic model to determine the directional dynamics of the test vehicle subjected to selected test manoeuvres and speeds. The directional response characteristics established from the simulation are compared to those obtained from the field tests.



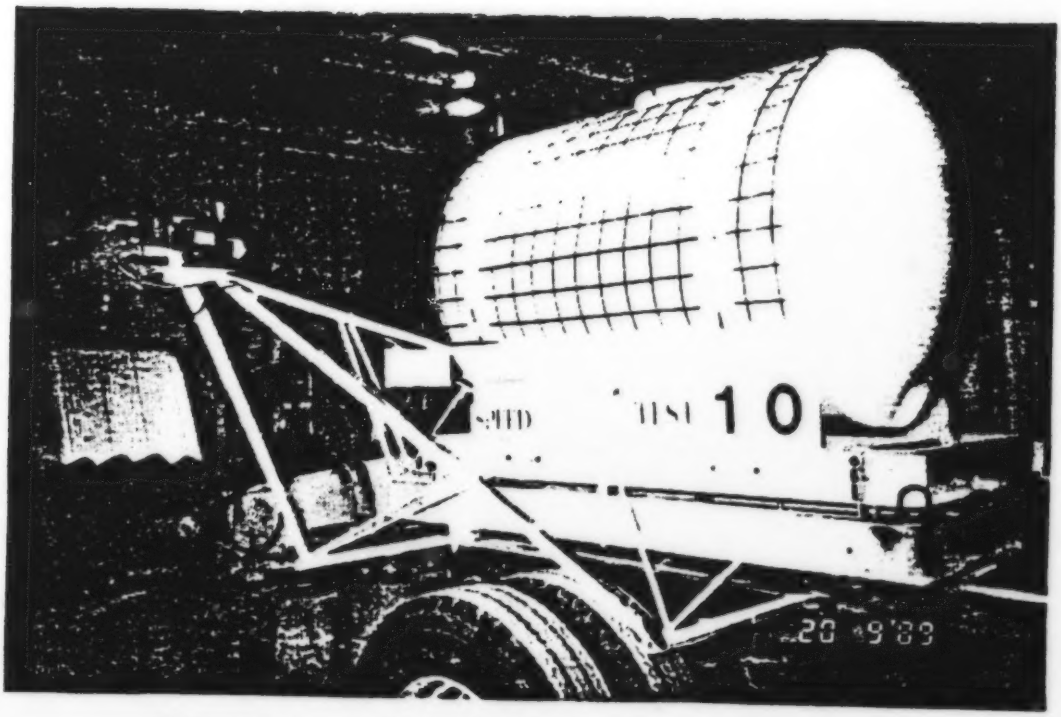


Figure 7.5: Pictorial views of the test vehicle.

7.4.1 30 M CONSTANT RADIUS TURN

The field test data was analyzed to determine the steer angle, roll angle, yaw angle and lateral acceleration response characteristics of the vehicle negotiating a 30 m constant radius turn. The repeatability of the test data was first examined by performing the right turn test four times. These tests were conducted with a 50% full tank and vehicle speed of 39 km/h. The test data obtained from these four tests are presented in Figure 7.6. The test results demonstrate a high degree of repeatability.

Computer simulations are conducted to evaluate the response characteristics of a 50%-filled tank vehicle negotiating a 30 m radius right turn at a constant speed of 39 km/h. The directional response characteristics of the tank vehicle are compared to those obtained from the field tests, as shown in Figure 7.7. The steer input to the simulation vehicle is derived from field measured front wheel steer angle, as shown in Figure 7.7. The field measured roll angle response of the test vehicle correlates reasonably well with the roll angle response obtained via computer simulation. Small discrepancies in magnitude, however, arise due to cross-slope of the ground and ground roughness. The maximum roll angle of the test vehicle reaches approximately 3 degrees while the simulation results indicate a maximum of approximately 2.8 degrees. The lateral acceleration response of the simulation and test vehicle correlate very well except for high frequency oscillations. These oscillations, in lateral acceleration response, arise due to the road roughness. The mean lateral acceleration response, however, correlates well with the simulation data. The maximum value of lateral acceleration encountered during the manoeuvre is approximately 0.45 g. The yaw angle response increases gradually and reaches a maximum value of 90 degrees for both the test and simulation vehicles.

A variation in vehicle speed influences the dynamic response of the tank truck. The lateral and vertical load shifts within the partially filled tank depend on lateral acceleration and thus vehicle speed. The analytical model of the tank truck was also validated for different vehicle speeds. The field test was conducted at a speed of 29 km/h for a 50%-fill condition. The simulation and test results were compared and are shown in Figure 7.8. As in the previous case, the computer simulation results show a good correlation with the field measured data. The peak values of roll angle and lateral acceleration are considerably lower in this case due to the reduced vehicle speed. The vehicle experiences peak roll angles around 2 degrees (experimental) and 1.5 degrees (simulation), while the lateral acceleration peaks at approximately 0.25 g for both the field test and simulation, when the steer angle reaches a peak value of 9 degrees.

It was pointed out earlier that an increase in fill height leads to a decrease in roll and lateral stability of the vehicle due to increased centre of mass height. To corroborate the analytical findings, field tests were conducted for a 70%-filled tank. Test and simulation results are presented in Figure 7.9. The figure reveals that the peak roll angle response of the test vehicle is around 4 degrees, which is larger than that attained for a 50% loaded vehicle (3 degrees). A comparison of Figures 7.7 and 7.9 reveals only a small change in the vehicle's response characteristics due to fill level variation from 50% to 70%. This is attributed to the fact that for the small

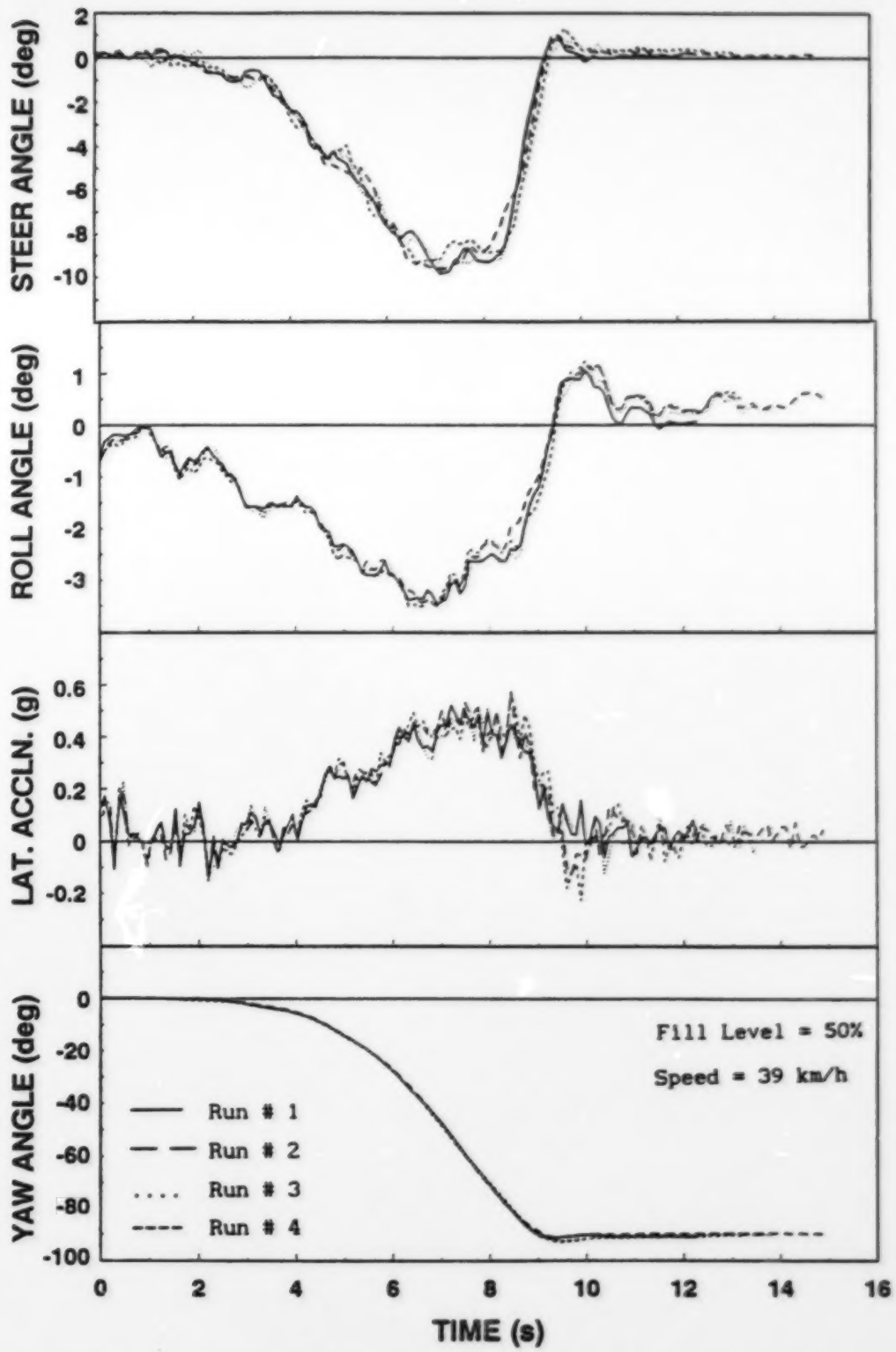


Figure 7.6: Repeatability of the 30 m turn radius test runs.

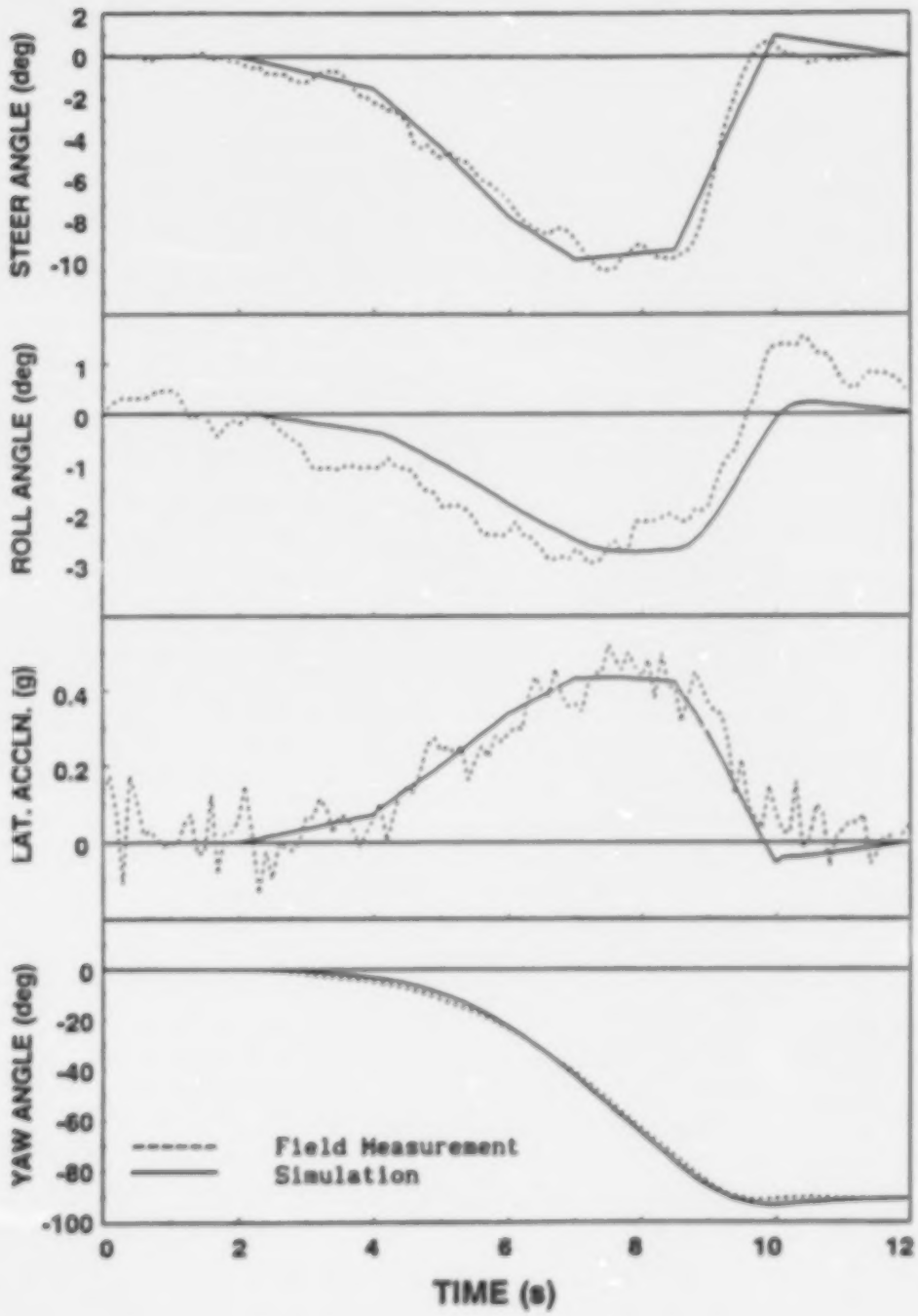


Figure 7.7: Comparison of experimental and simulation response of 50% filled tank vehicle (30 m radius turn; speed = 39 km/h).

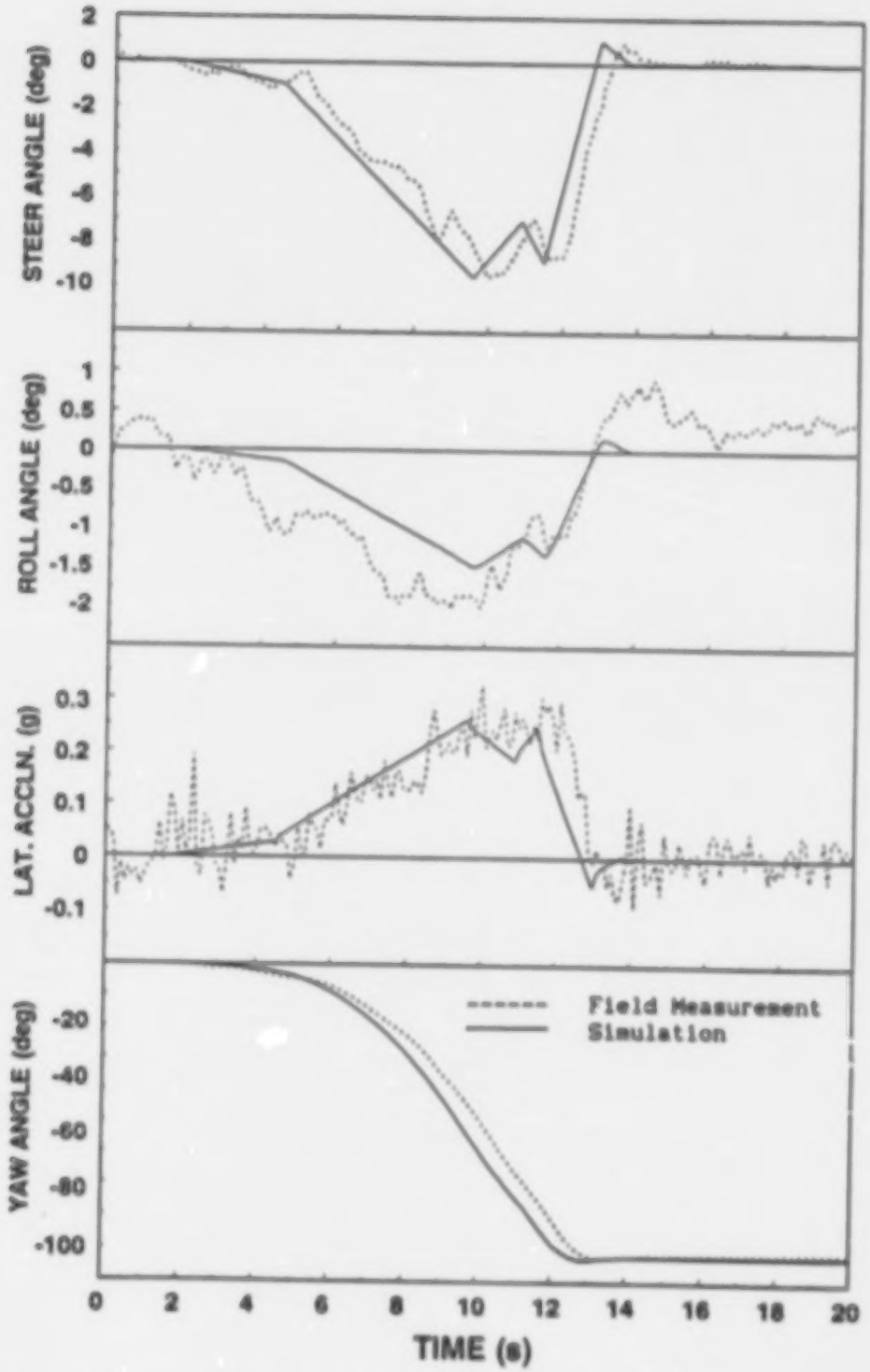


Figure 7.8: Comparison of experimental and simulation response of 50% filled tank vehicle (30 m radius turn; speed = 29 km/h).

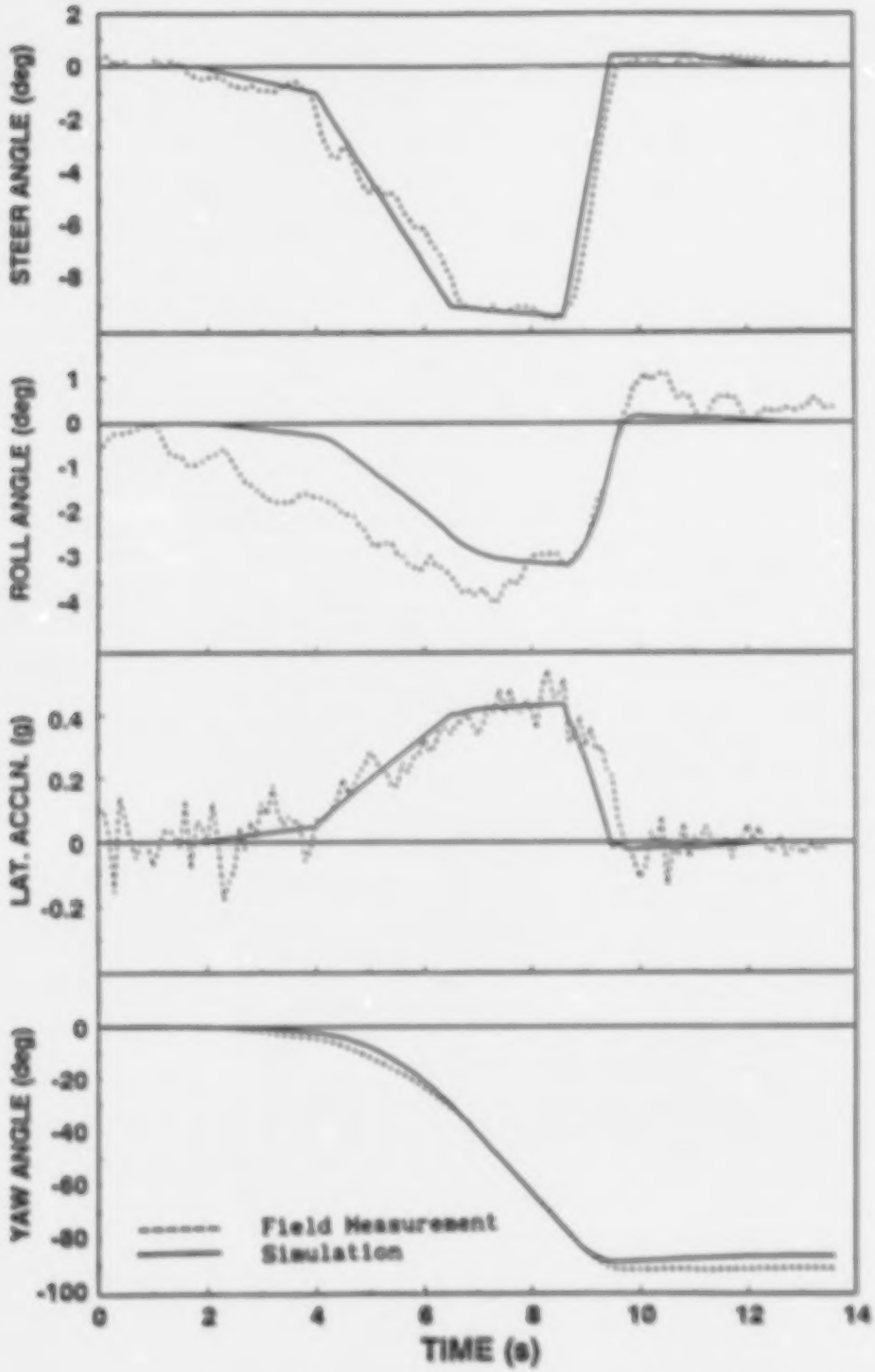


Figure 7.9: Comparison of experimental and simulation response of 70% filled tank vehicle (30 m radius turn; speed = 39 km/h).

sized tank vehicle considered, an increase in the fill level yields only a small increase in the payload.

7.4.2 LANE CHANGE MANOEUVRE

The directional response of the test vehicle is investigated for a typical lane change manoeuvre in order to further validate the analytical model. The computer simulations are carried out for the steer input derived from field measurements. The tests are carried out for various values of fill level, vehicle speed, and gate width. Figure 7.10 presents a comparison of the experimental and simulation results for the 50%-filled tank truck, negotiating a 3 m (10 feet) lane change at a vehicle speed of 45 km/h. The gate width for the manoeuvre is selected as 15 m (50 feet). The roll angle, lateral acceleration and yaw angle response characteristics obtained via computer simulation and field tests are presented in Figure 7.10. Although the computer simulation results exhibit a high degree of correlation with the field measured response characteristics, the peak values of roll angle, lateral acceleration and yaw angle response of the test vehicle differ from those of the simulation vehicle. The peak roll response of the tank vehicle is approximately 0.6 degrees larger than that established from the simulation results. Similarly, the yaw response is found to be larger by approximately 2 degrees. Moreover, the vehicle response characteristics do not reach the steady-state zero position at the end of the test run, since the data acquisition was stopped prior to the completion of the corrective steering action.

The influence of vehicle speed on directional response of the tank vehicle is analyzed by reducing the vehicle speed to 35 km/h under identical conditions of fill level and vehicle path. Figure 7.11 presents the comparison of test and simulation results. Decrease in vehicle speed increases the simulation time to approximately 10 seconds. The data acquisition was stopped prior to the completion of the corrective action of the steering, thus the response characteristics did not attain the steady-state zero response at the end of 10 seconds. The peak roll angle and lateral acceleration response of the test vehicle correlate reasonably well with the simulation results.

Figure 7.12 presents the response characteristics of a 50%-filled tank vehicle for a lane change manoeuvre with a 21 m (70 feet) gate at a speed of 45 km/h. The increase in the gate width from 15 m (50 feet) to 21 m (70 feet) reduces the maximum steer value required to negotiate the turn from 6 degrees to approximately 2.5 degrees, as shown in Figure 7.12. The corresponding peak value of yaw angle reduces from 14 degrees to 9 degrees while the roll angle and lateral acceleration decrease from 2 degrees to 1 degree, and from 0.2 g to 0.15 g, respectively. The experimental and simulation results seem to compare very well except for the roll angle response which is again attributed to the cross-slope of the road surface.

The directional response characteristics of the 70%-filled tank vehicle for a 15 m (50 feet) lane change manoeuvre conducted at a vehicle speed of 45 km/h are presented in Figure 7.13. The field measured response characteristics correlate very well with the simulation results, and a comparison of Figures 7.10 and 7.13 reveals that an increase in fill height

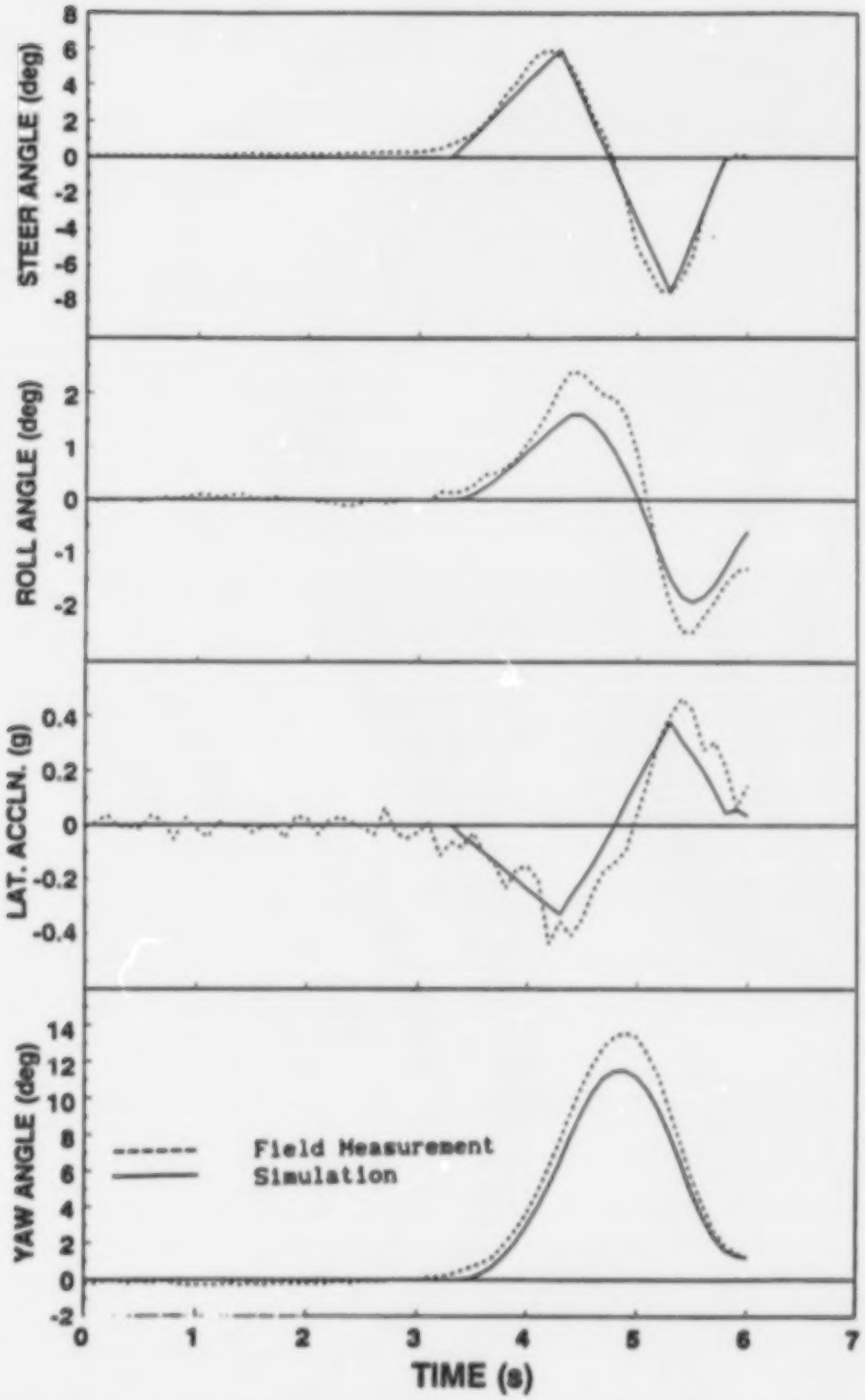


Figure 7.10: Comparison of experimental and simulation response of 50% filled tank vehicle (15 m lane change; speed = 45 km/h).

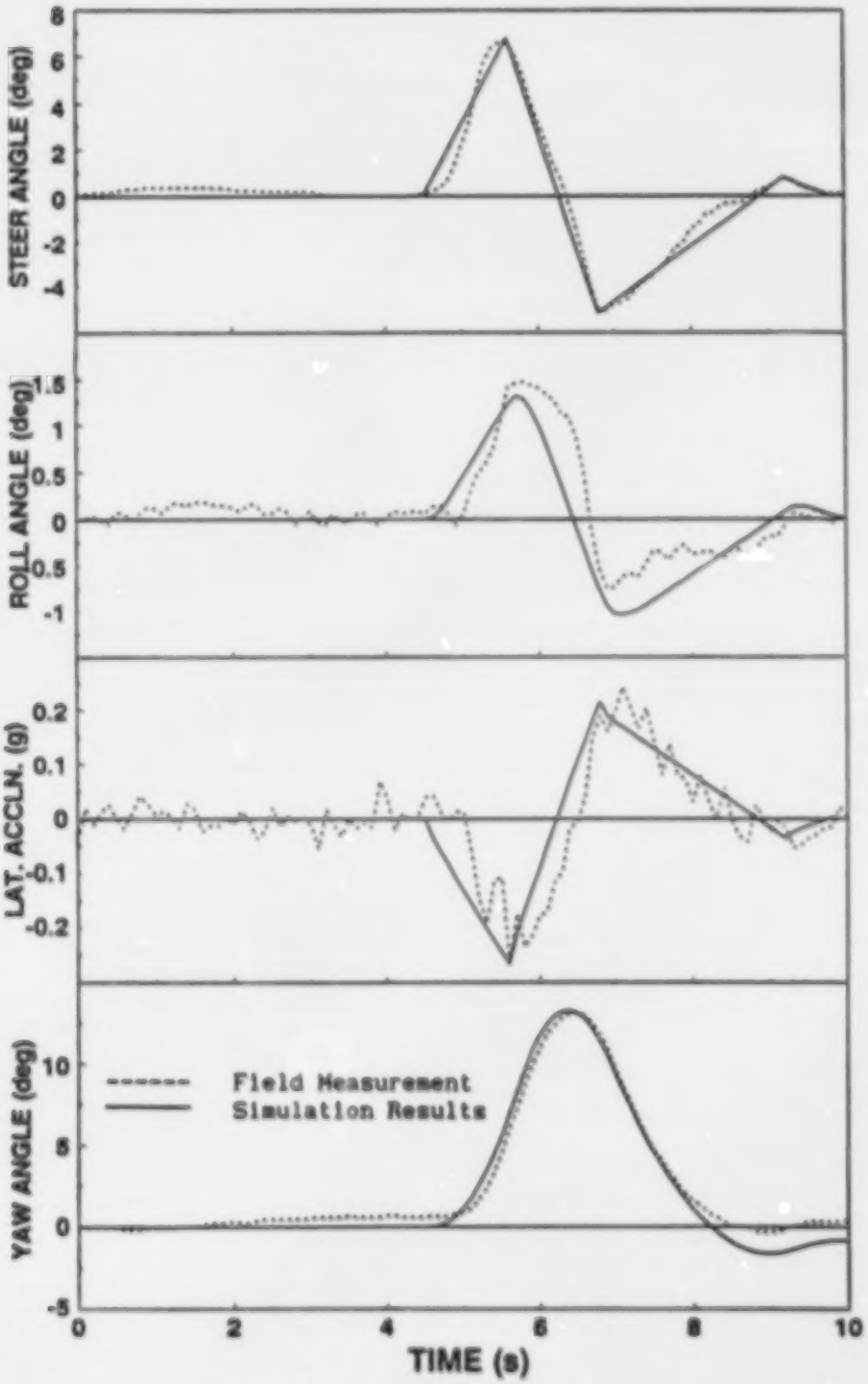


Figure 7.11: Comparison of experimental and simulation response of 50% filled tank vehicle (15 m lane change; speed = 35 km/h).

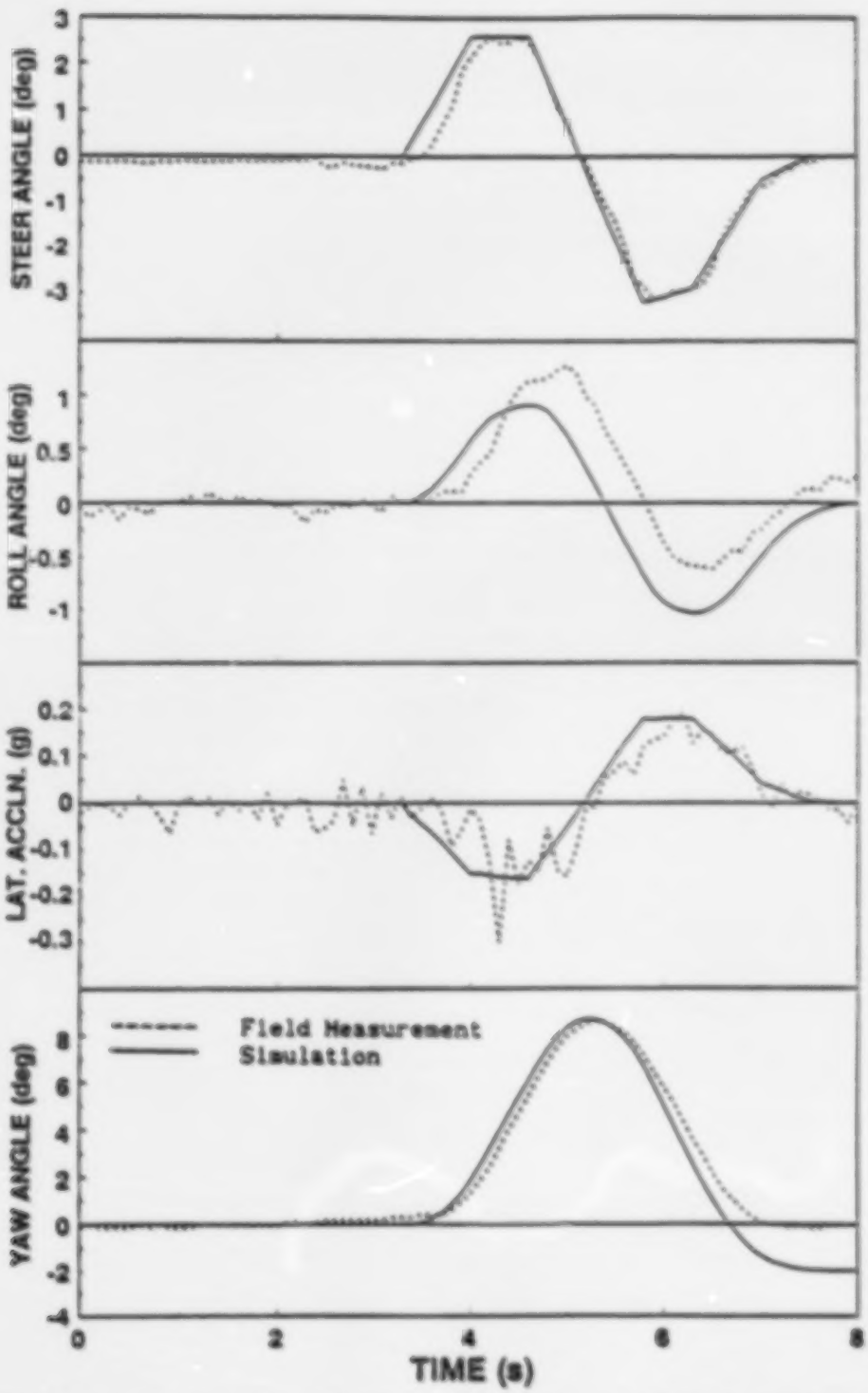


Figure 7.12 Comparison of experimental and simulation response of 50% filled tank vehicle (21 m lane change; speed = 45 km/h).

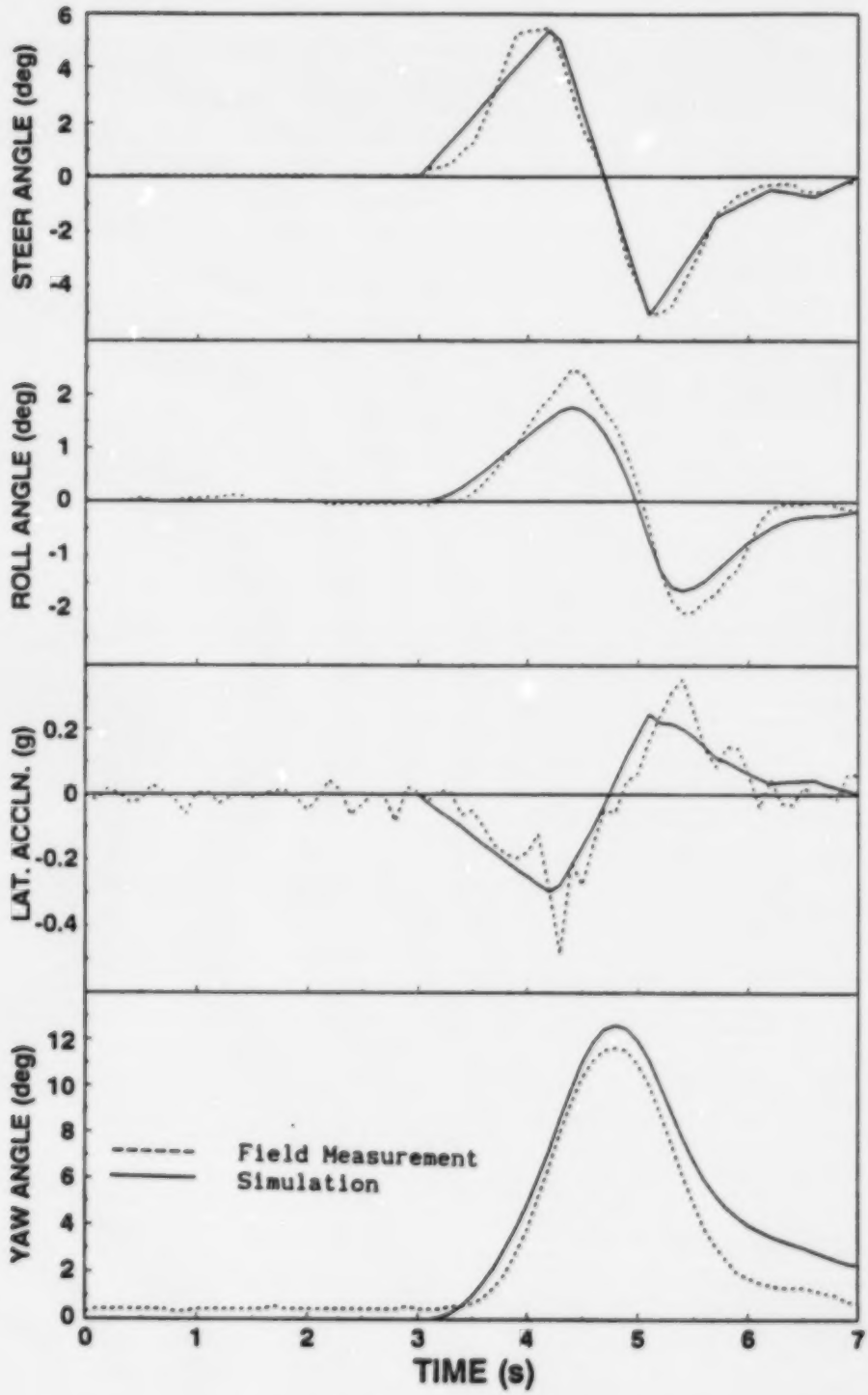


Figure 7.13: Comparison of experimental and simulation response of 70% filled tank vehicle (15 m lane change; speed = 45 km/h).

does not alter the response values appreciably, since the corresponding increases in total payload and overall centre of mass height are relatively small for the tank vehicle tested.

8. CONCLUSIONS

The adverse influence of liquid slosh on the static and dynamic stability limits of partially filled tank vehicles was investigated through computer simulation and field testing. Directional dynamics and overturning stability limits of tractor-semitrailer and B-train tank vehicles were investigated in view of various operational and tank design factors. The study comprised five sequential phases. In the initial phase, haulers of fuel oils and chemicals and tank manufacturers across Canada were surveyed to identify commonly used vehicle configurations and problems of concern. Records of highway accidents involving tank vehicles were reviewed to further identify the problems of primary concern. From these surveys, it was concluded that:

(a) Tractor-semitrailer (five- and six-axles) tank vehicles and seven- or eight-axle B-train combinations are the most often used vehicles to haul dangerous liquid products.

(b) Cleanbore circular and compartmented modified oval tanks are most commonly used in transportation of dangerous liquid products.

(c) Vehicle rollover remains the primary problem of concern.

The study was thus directed towards the development of computer simulation software to investigate static and dynamic roll stability of tractor-semitrailer and B-train tank vehicle combination with cleanbore or compartmented circular and modified oval tanks. Research literature on the dynamics of heavy vehicles carrying rigid or liquid cargo was reviewed during the second phase of the study and it was determined that existing analytical models lack comprehensive treatment of fluid slosh behaviour.

A steady-state model of a partially filled, arbitrarily shaped tank cross-section was developed and integrated to the kineto-static roll plane model of the tank vehicle to investigate the overturning limits of tank vehicles. Computer simulations were performed to study the influence of various tank design and operational factors. Following conclusions were reached:

(a) Lateral load transfer within a partially filled tank is strongly related to tank geometry, fill level and lateral acceleration.

(b) Overturning limits of partially filled tank vehicles are considerably lower than those of equivalent rigid cargo vehicles.

(c) Magnitude of lateral load transfer increases with reduced fill levels.

(d) Lateral load shift within modified oval and square tanks is considerably larger than that within a circular tank. Tank vehicles with modified oval and square tanks thus reveal lower overturning limits.

(e) Tank vehicles exhibit lowest overturning limit around 40%-fill level when compared to those of equivalent rigid cargo vehicles.

(f) Under constant axle loads, overturning limits of tank vehicles decrease with low fill level, while the overturning limits of corresponding equivalent rigid cargo vehicles increase.

(g) Modified oval and square tanks exhibit improved overturning limits while carrying lighter liquids, whereas circular tanks show better stability for denser liquids.

(h) Overturning limits of partially filled tank vehicles can be improved considerably utilizing compartmented tanks.

A quasi-dynamic yaw and roll model of a tank vehicle was developed during the third phase by integrating a steady-state fluid slosh model to the vehicle model. Computer simulations were performed to determine the directional response characteristics of candidate vehicles for steady and transient directional manoeuvres and compared to those of equivalent rigid cargo vehicles to demonstrate the influence of liquid load shift. Parametric sensitivity analyses were conducted to study the influence of fill level, axle load, and vehicle speed on the directional response of tank vehicle combinations. The following conclusions were drawn:

(a) Dynamic load transfer, encountered during a constant steer manoeuvre, yields unequal distribution of cornering forces between the two tracks, leading to considerable deviation in the path followed by tank vehicle compared to that of an equivalent rigid cargo vehicle.

(b) Dynamic load transfer is strongly related to tank geometry, fill level, vehicle speed and steer input.

(c) During a constant steer manoeuvre, an increase in vehicle speed from 60 km/h to 90 km/h, leads to increased roll and lateral acceleration response and possible rollover of the five-axle tractor-tank-semitrailer while the equivalent rigid cargo vehicle exhibits stable characteristics.

(d) A comparison of the dynamic characteristics of 5-axle and 6-axle tractor-semitrailer tank vehicles, carrying maximum permissible load, reveals that 6-axle tank vehicles are more stable than the 5-axle tank-semitrailer vehicles.

(e) Partially filled tank vehicles as well as the equivalent rigid cargo vehicles exhibit stable behaviour during lane change manoeuvres at typical highway speeds. The roll and lateral acceleration response of the partially filled tank vehicles, however, are considerably higher than those of the equivalent rigid cargo vehicles.

(f) Partially filled tank vehicles are less stable than the equivalent rigid cargo vehicles in an evasive manoeuvre performed at highway speeds. The excessive load shift occurring during the evasive manoeuvre can lead to wheel lift-off and possible vehicle rollover.

(g) Roll angle and lateral acceleration amplification factors for a B-train are relatively large indicating the likelihood of rear trailer rollover.

A comprehensive dynamic fluid slosh model was developed during the fourth phase of the study to investigate dynamic characteristics of slosh forces and moments. The directional response characteristics of tank vehicles incorporating the dynamic liquid slosh model are compared to those of the vehicles incorporating the steady-state liquid slosh model in order to demonstrate the influence of dynamic slosh forces on the vehicle stability.

Computer simulations of a tank vehicle model (incorporating the dynamic fluid slosh model) performed for a steady steer input indicate that the directional response oscillates at its fundamental mode of vibration around a mean value predicted by the quasi-dynamic model. The frequency of oscillation lies close to the value derived from linear theory. The simulation results reveal that the quasi-dynamic vehicle model can predict the directional response almost as accurately as the comprehensive fluid slosh model. The quasi-dynamic model, however, overestimates the response characteristics in case of low frequency steer inputs, while a high degree of correlation is obtained for steer frequencies corresponding to typical highway manoeuvres.

During the final phase of the study computer simulation model outputs were validated by comparing them to results obtained from field tests conducted on a tank truck equipped with a cylindrical tank. Directional response characteristics were measured for typical right turn and lane change manoeuvres at various vehicle speeds and fill levels, and compared with those obtained from the computer simulation. Simulation results correlated quite well with the field-measured results. This correlation provides the necessary confidence in computer models for predicting directional dynamics of tank vehicles.

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